The GFDL Coupled Data Assimilation System Using a Parallelized Ensemble Filter for Climate Detection and Forecast Initialization

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Ocean Analyses Using Models and Data:

- ✓ One side: facts -
  - Climate model: inevitable drift from reality due to incomplete understanding of climate change and its modeling
  - Observations: inevitable instrument and representation errors
- ✓ The other side: we need -
  - Analysis of climate variability (Carbon/heat uptake, circulation, …)
  - **<u>Detection of climate change</u>**
  - **Observing system evaluation**/design
  - **Forecast initialization (SI, decadal)**
  - Model evaluation, forecast verification
  - Model parameter estimation

OUTLINE

- ✓ Can ocean data assimilation detect the signal of climate change? Are available observations sufficient?

  Idealized 'twin' experiments based on a real ocean obs network:
  - Climate detection by data assim: 'to be' or 'not to be'?
  - Using $20^{th}/21^{st}$ century obs network: Observing system evaluation

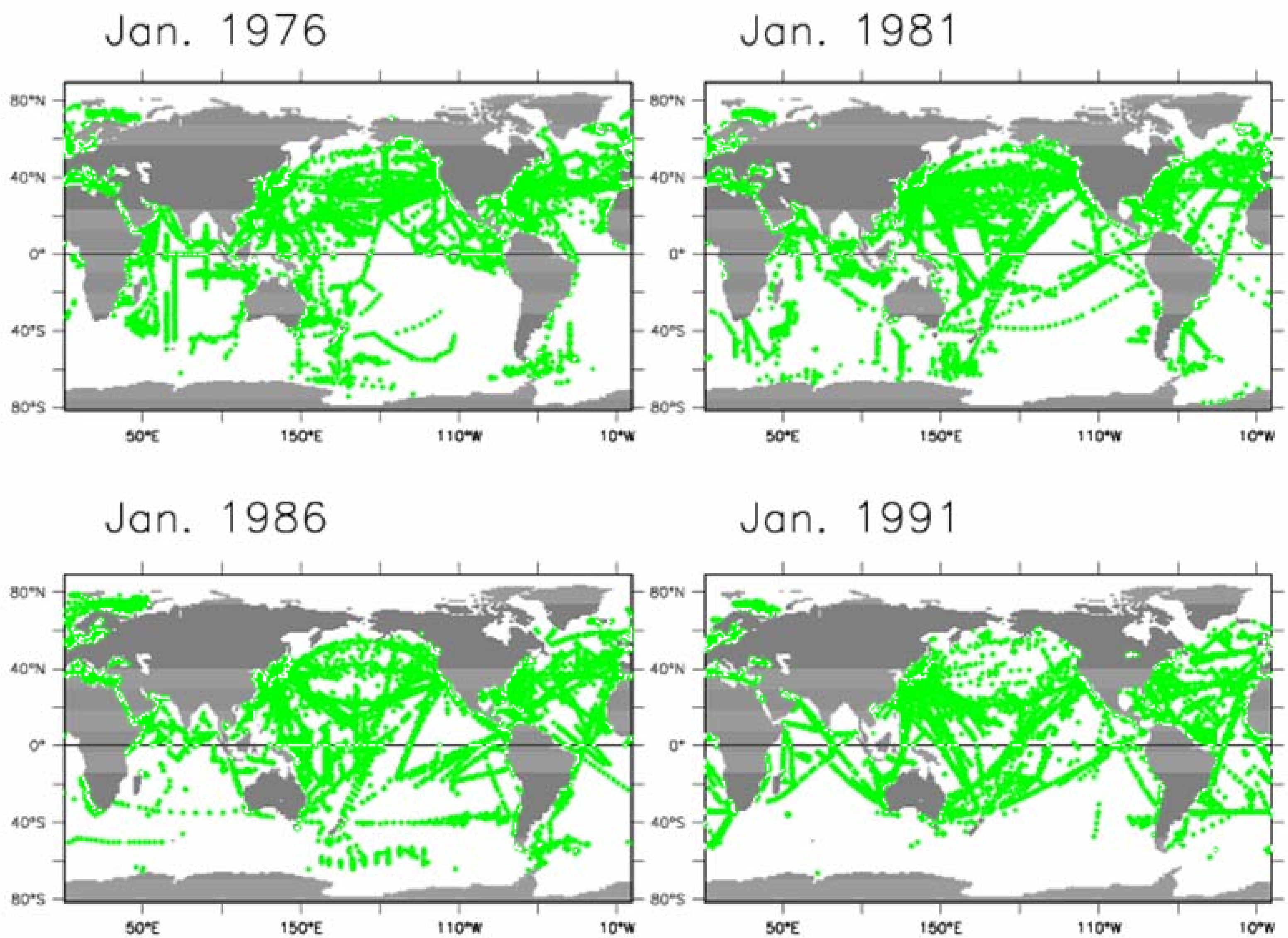
- ✓ A 'super-parallelized' ensemble filter with the GFDL's fully-coupled GCM (CM2)
  - Importance of maintaining the T-S relationship in Oceanic Data Assimilation (ODA)
  - Importance of maintaining geostrophic balance in Atmospheric Data Assimilation (ADA)

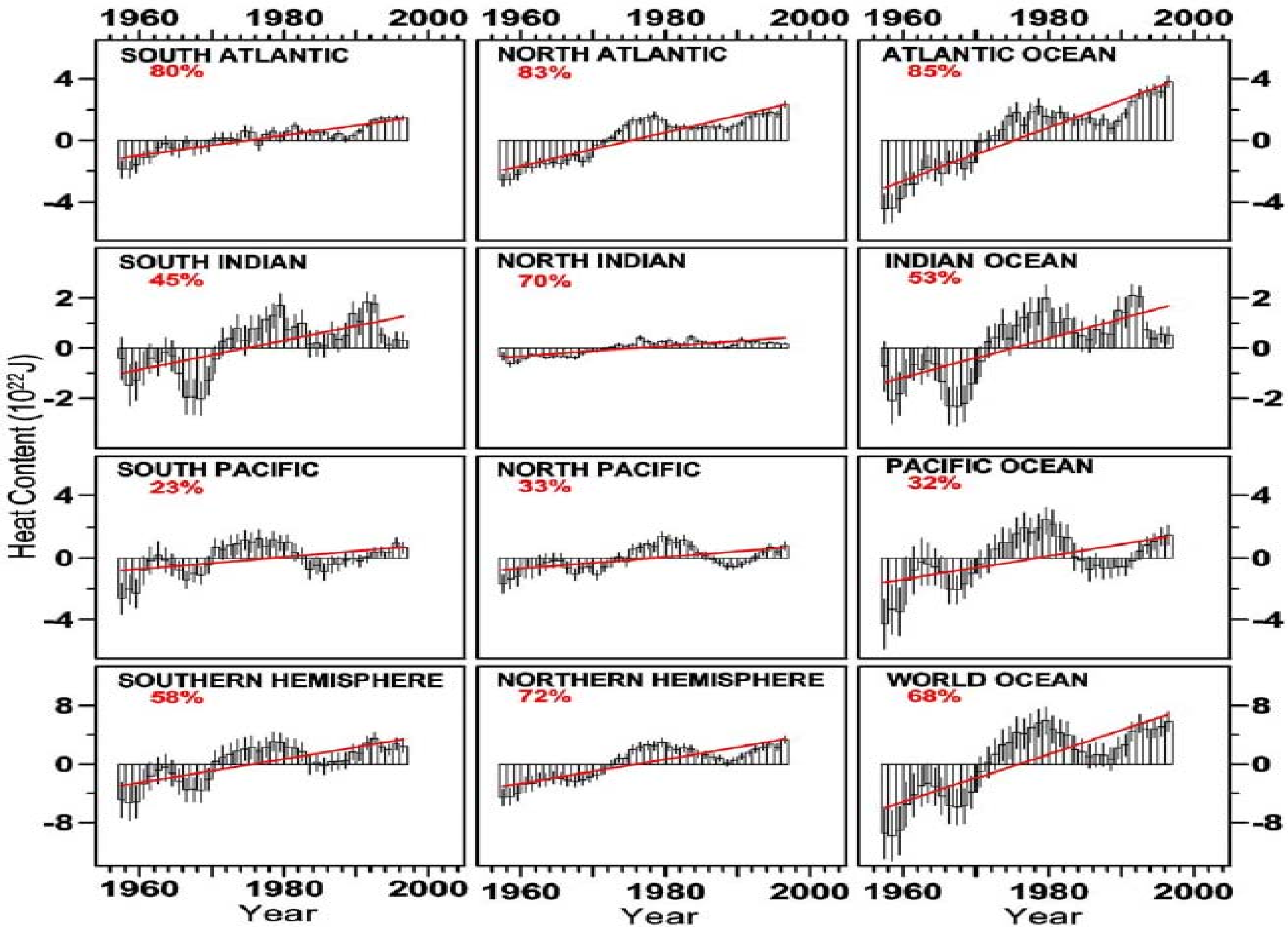
- ✓ Detection of climate changes using $20^{th}/21^{st}$ century ocean observational networks
  - ENSO variability
  - Multi-decadal variability of ocean heat content and salinity
  - Estimation of Atlantic meridional overturning circulation (MOC)

- ✓ Impact of ODA's initialization on SI forecasts
  - Vertical structure of forecasted NINO3, NINO3.4 and NINO4 temperature
  - Forecast skills in NINO3, NINO3.4 and NINO4
  - Case study for a strong ENSO warm event

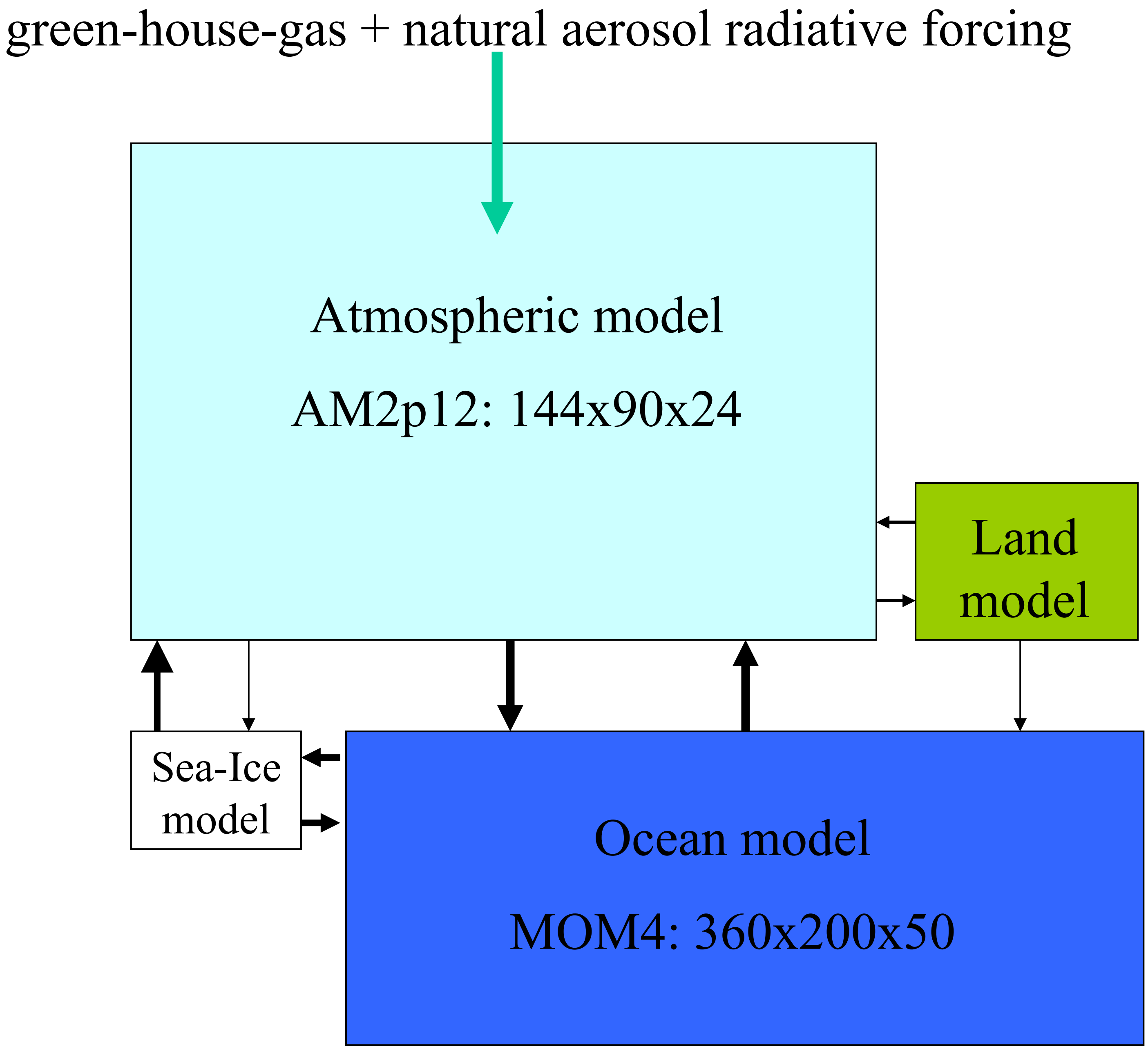
- ✓ Discussions and future directions

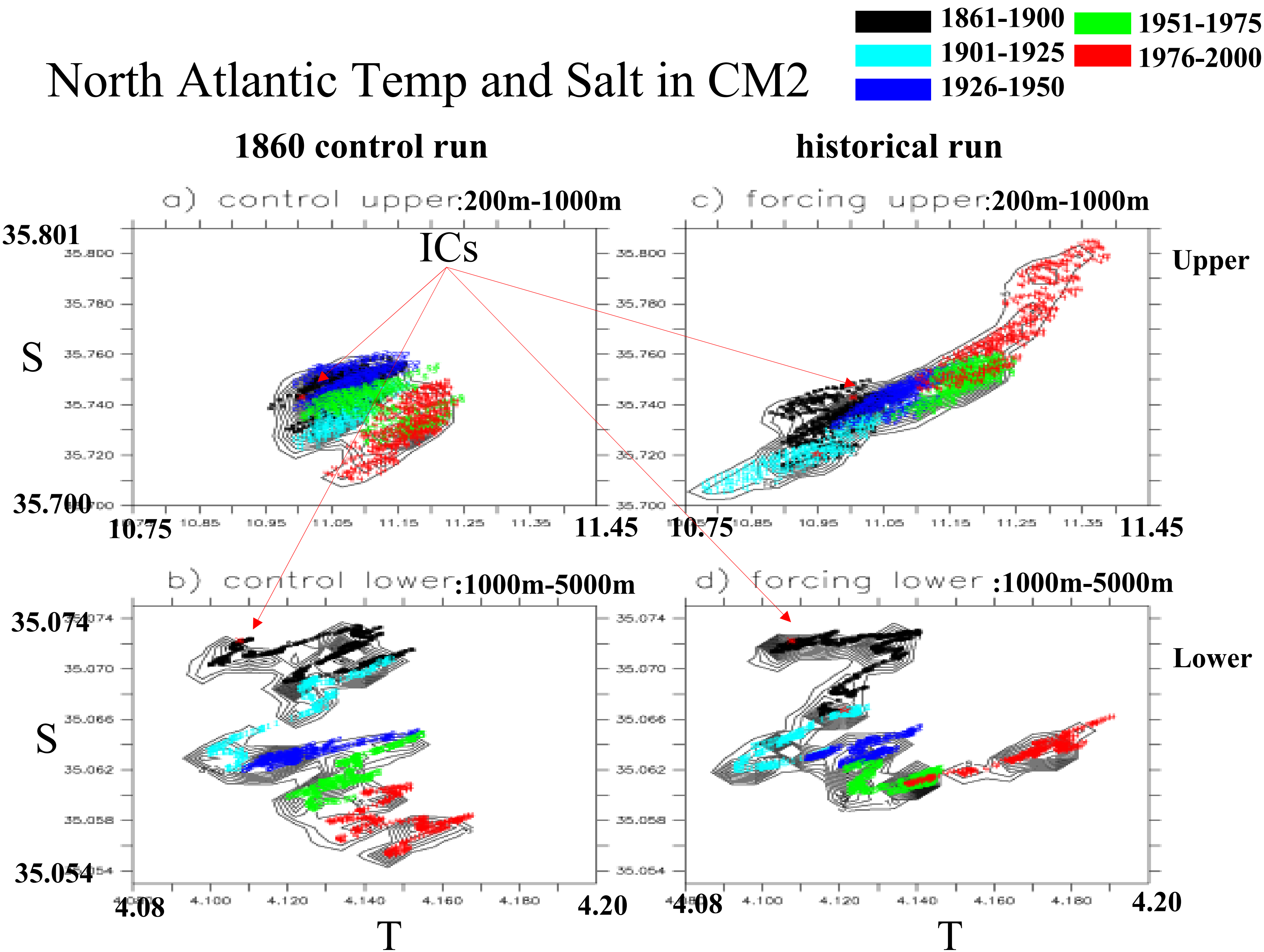
Given ocean temperature observational network
Can we assess climate change in the 20th Century?





(Levitus et al. 2005)

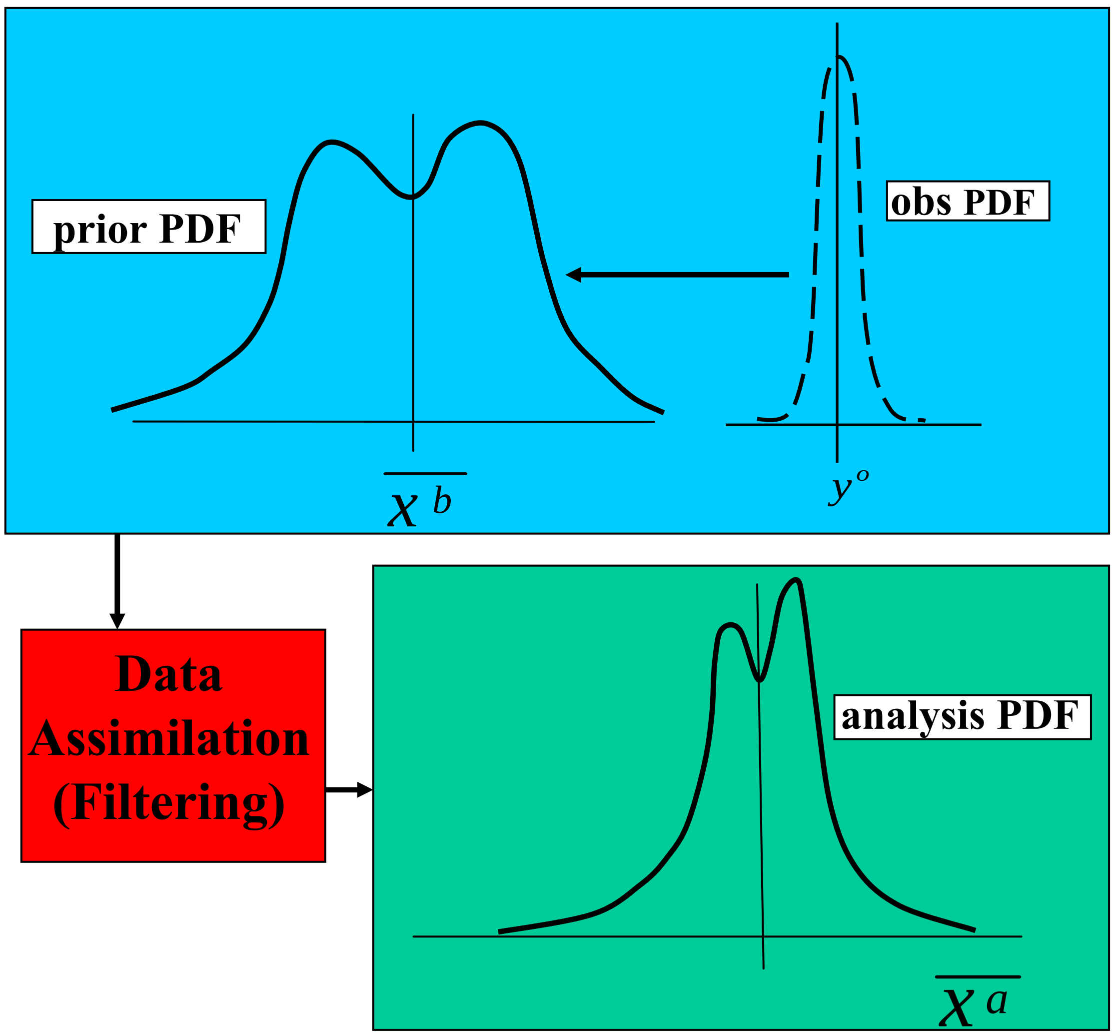

green-house-gas + natural aerosol radiative forcing
Atmospheric model
AM2p12: 144x90x24
Land model
Sea-Ice model
Ocean model
MOM4: 360x200x50



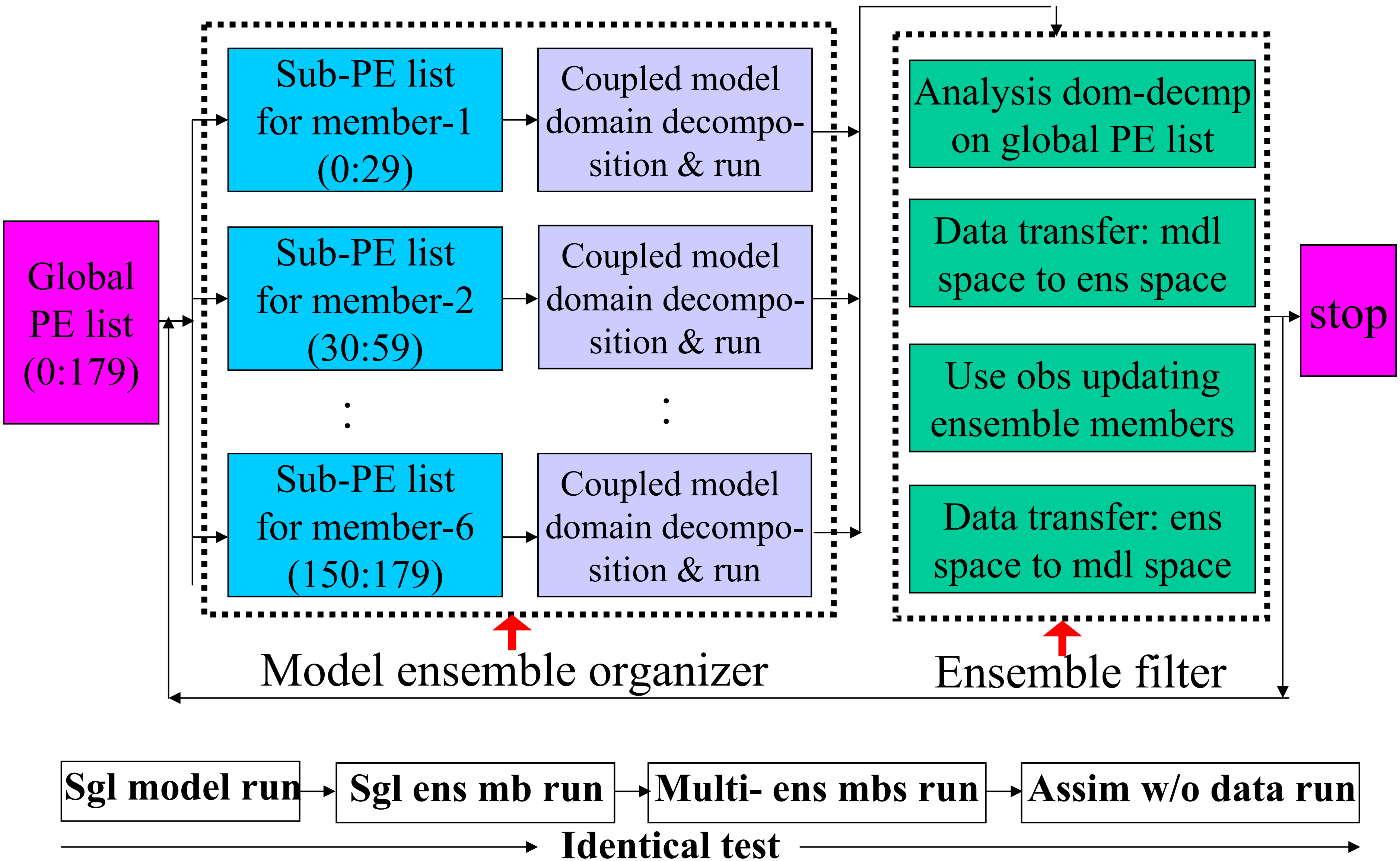
1861-1900
1901-1925
1926-1950
1951-1975
1976-2000
North Atlantic Temp and Salt in CM2
1860 control run
historical run
a) control upper:200m-1000m
c) forcing upper:200m-1000m
ICs
Upper
Lower
S
35.801
35.700
10.75
11.45
b) control lower:1000m-5000m
d) forcing lower :1000m-5000m
35.074
35.054
4.08
4.20
T

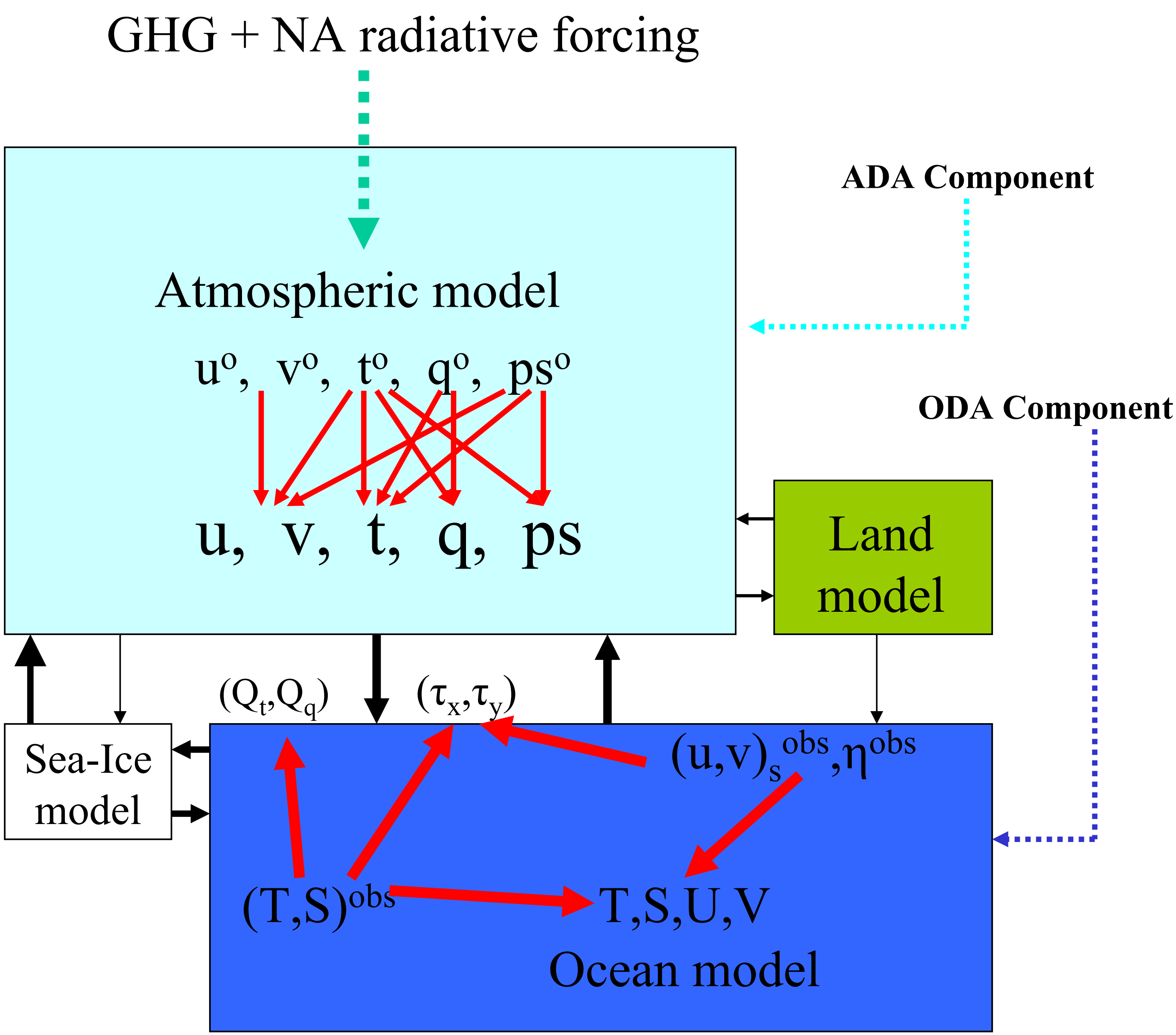
$$\overbrace{d\mathbf{x}_t / dt = f(\mathbf{x}_t, t)}^{\text{Deterministic (being modeled)}} + \overbrace{\mathbf{G}(\mathbf{x}_t, t)\mathbf{w}_t}^{\text{Uncertain (stochastic)}}$$

- ✓**Atmospheric internal variability**
- ✓**Ocean internal variability (model does not resolve)**



CM2 ensemble filter:
PE grouping and domain decomposition





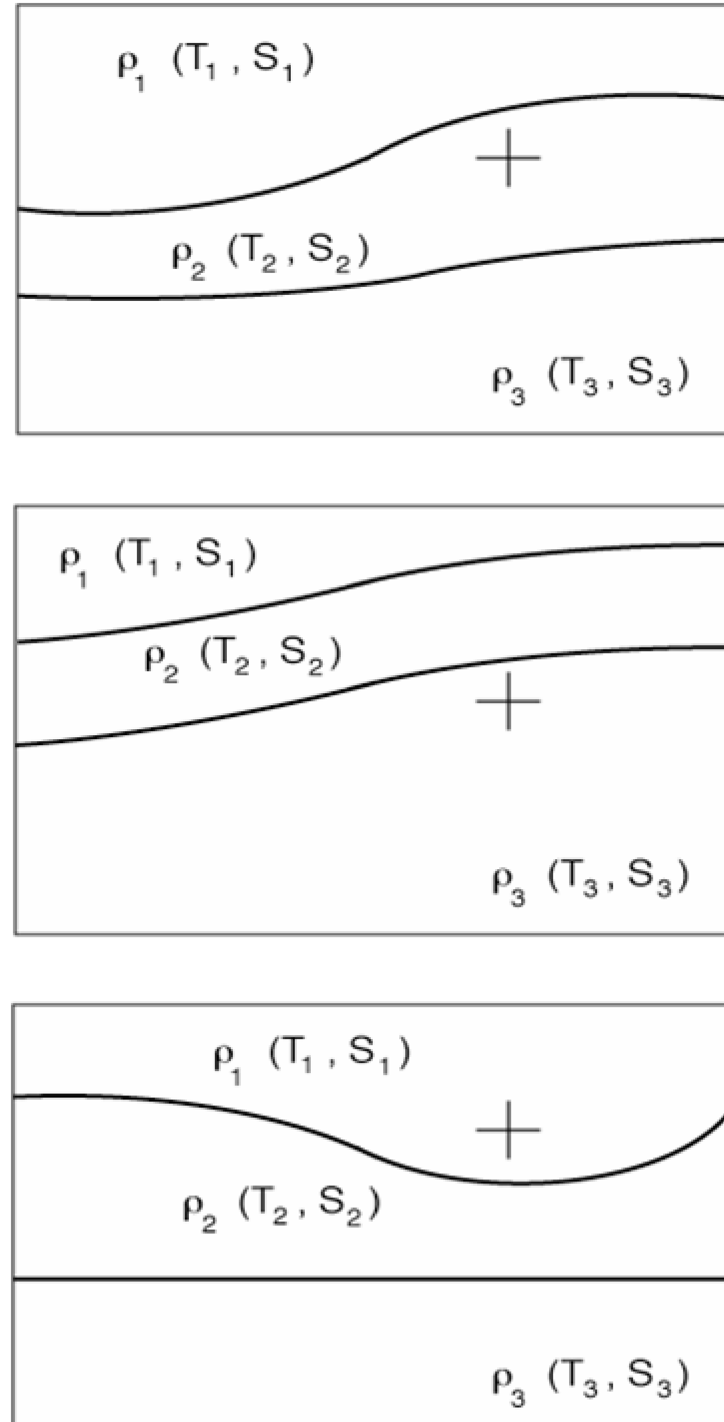
GHG + NA radiative forcing
ADA Component
ODA Component
Atmospheric model
u^o, v^o, t^o, q^o, ps^o
u, v, t, q, ps
Land model
Sea-Ice model
(Q_t,Q_q)
(τ_x,τ_y)
$(u,v)_s^{obs}$, η^{obs}
$(T,S)^{obs}$
T,S,U,V
Ocean model

Importance of maintaining the T-S relation

1) **Isopycnal nature of water movements**

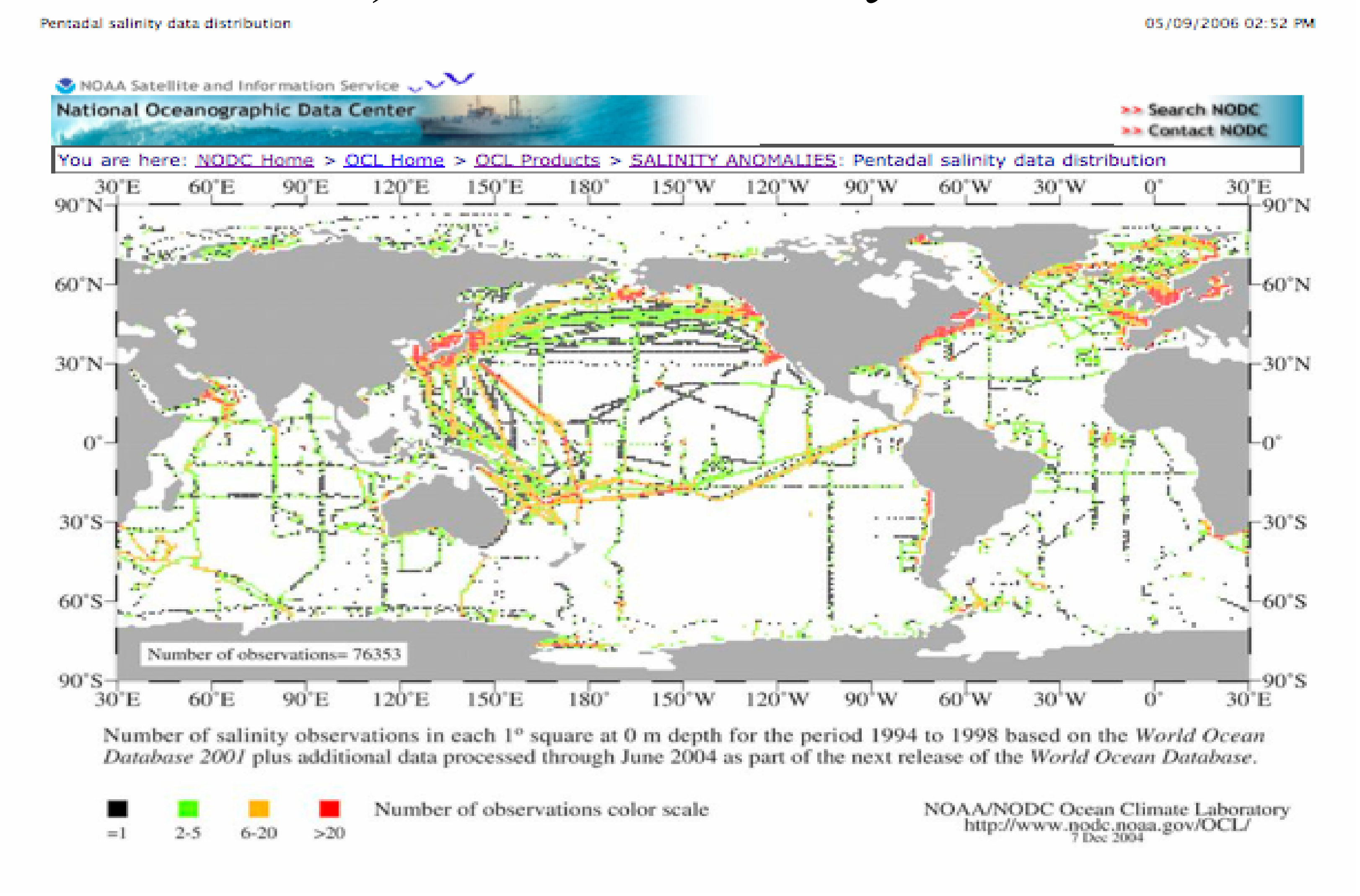
Fact: over the 20th century, salinity observations are very sparse.

We need a methodology to maintain T-S relationship where only T is observed.



Importance of maintaining the T-S relation

2) Pentadal Salinity Obs

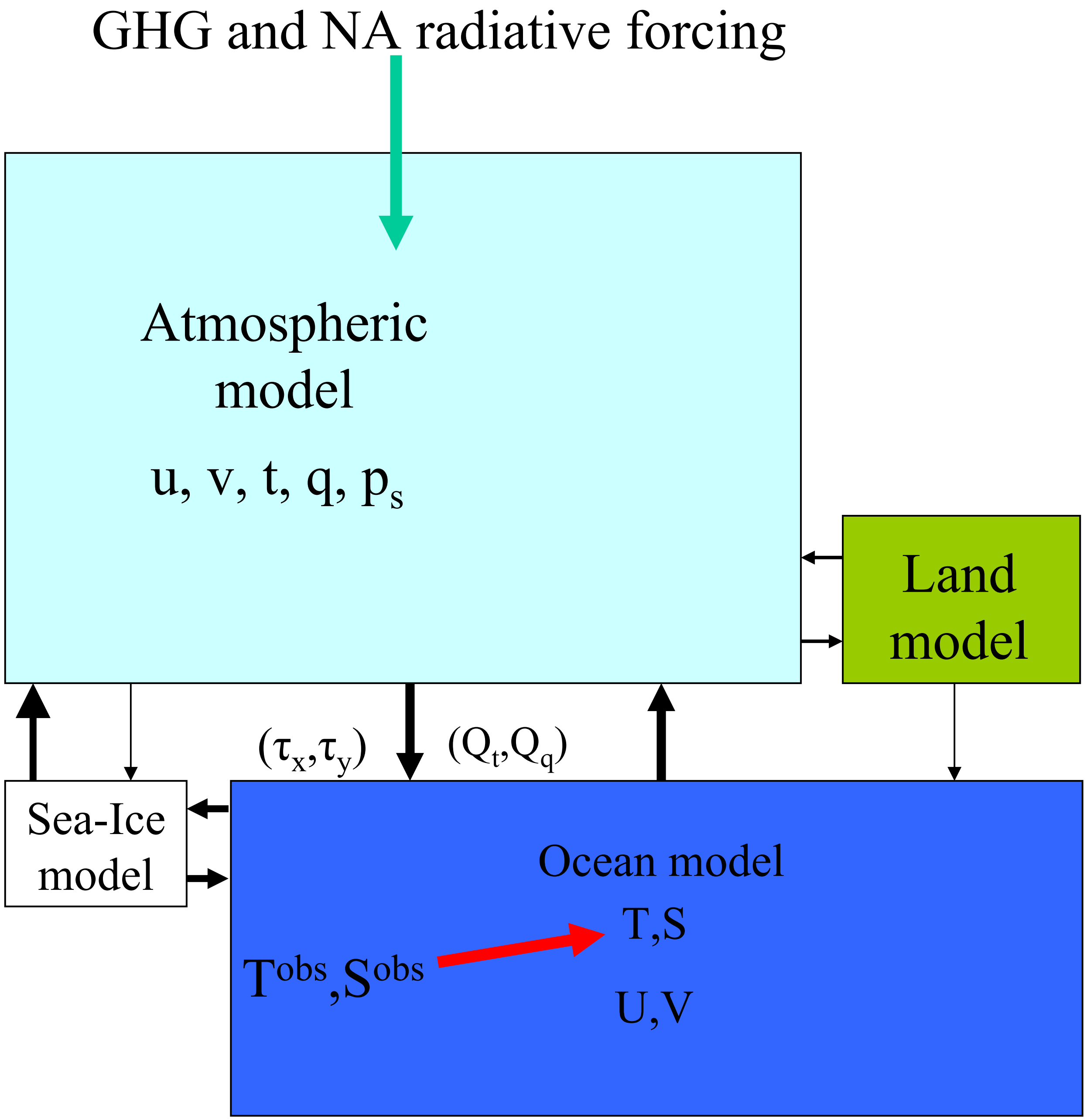


Importance of maintaining the T-S relation

3) test cases : using 1991 month mean data

- ✓ Idealized twin experiments: perfect model/observations
- ✓ Assimilation Model: CM2 with GHG +NA radiative forcing
- ✓ Observations: Project Jan., 1991 to Dec., 1991 CM2.0 IPCC historical run monthly mean temp/salt onto ocean XBT network, plus a white noise [$N_T(0,0.5)$ and $N_S(0,0.1)$]
- ✓ Initialize the model from arbitrary initial conditions (01/01/95)
- ✓ Test cases:
  1) T^{obs} -> T (T2T): Only allow temperature obs to correct temperature
  2) T^{obs} -> T,S (T2TS): Based on 1), using cov(T,S) to correct salinity also
  3) T^{obs},S^{obs} -> T,S (TS2TS): Using (T,S) obs and cov(T,S) to correct T & S

Question: How does the filter converge to the truth?



GHG and NA radiative forcing
Atmospheric model
u, v, t, q, p_s
Land model
(τ_x,τ_y)
(Q_t,Q_q)
Sea-Ice model
Ocean model
T,S
T^{obs},S^{obs}
U,V

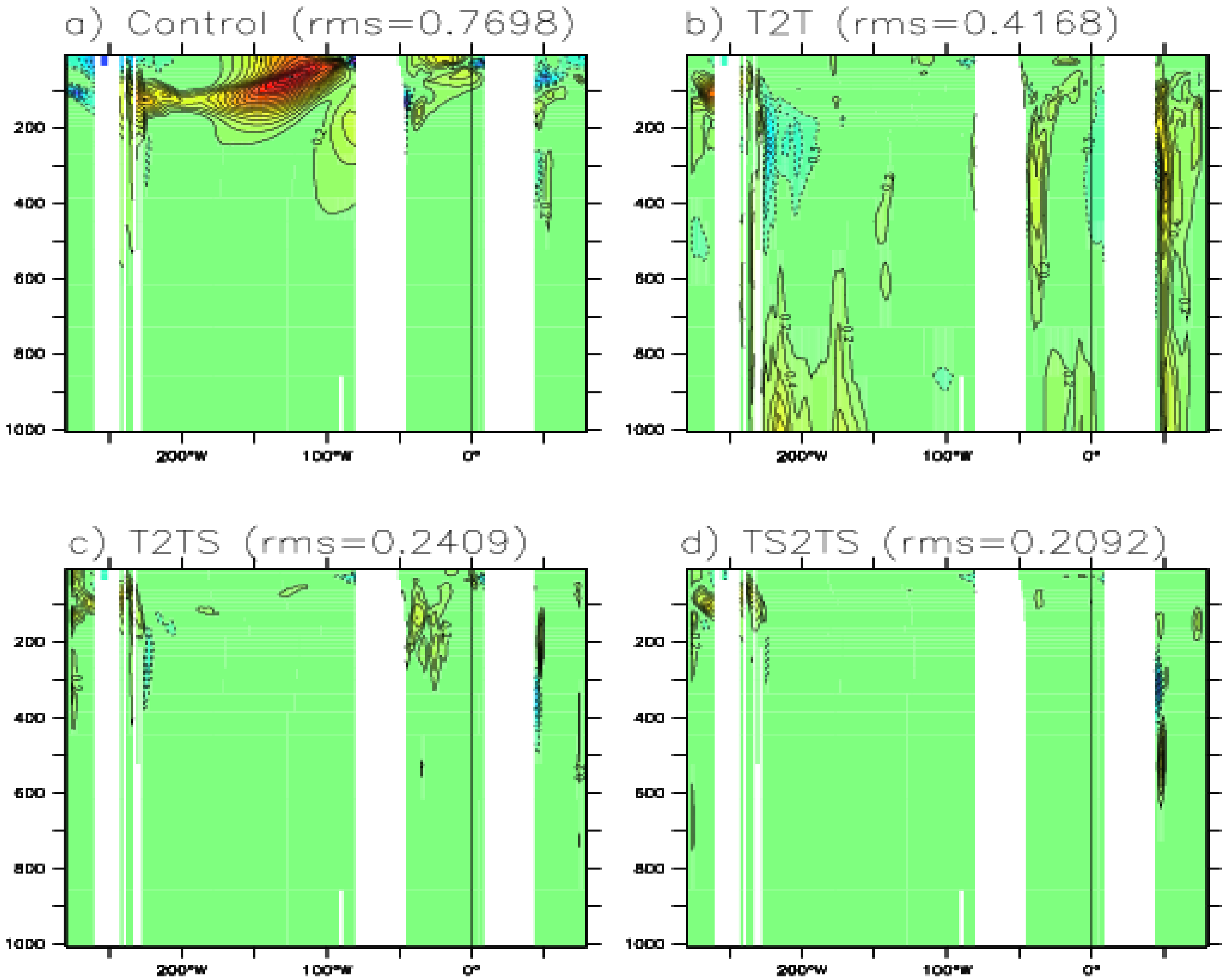
Ocean temperature errors at equator

CTL

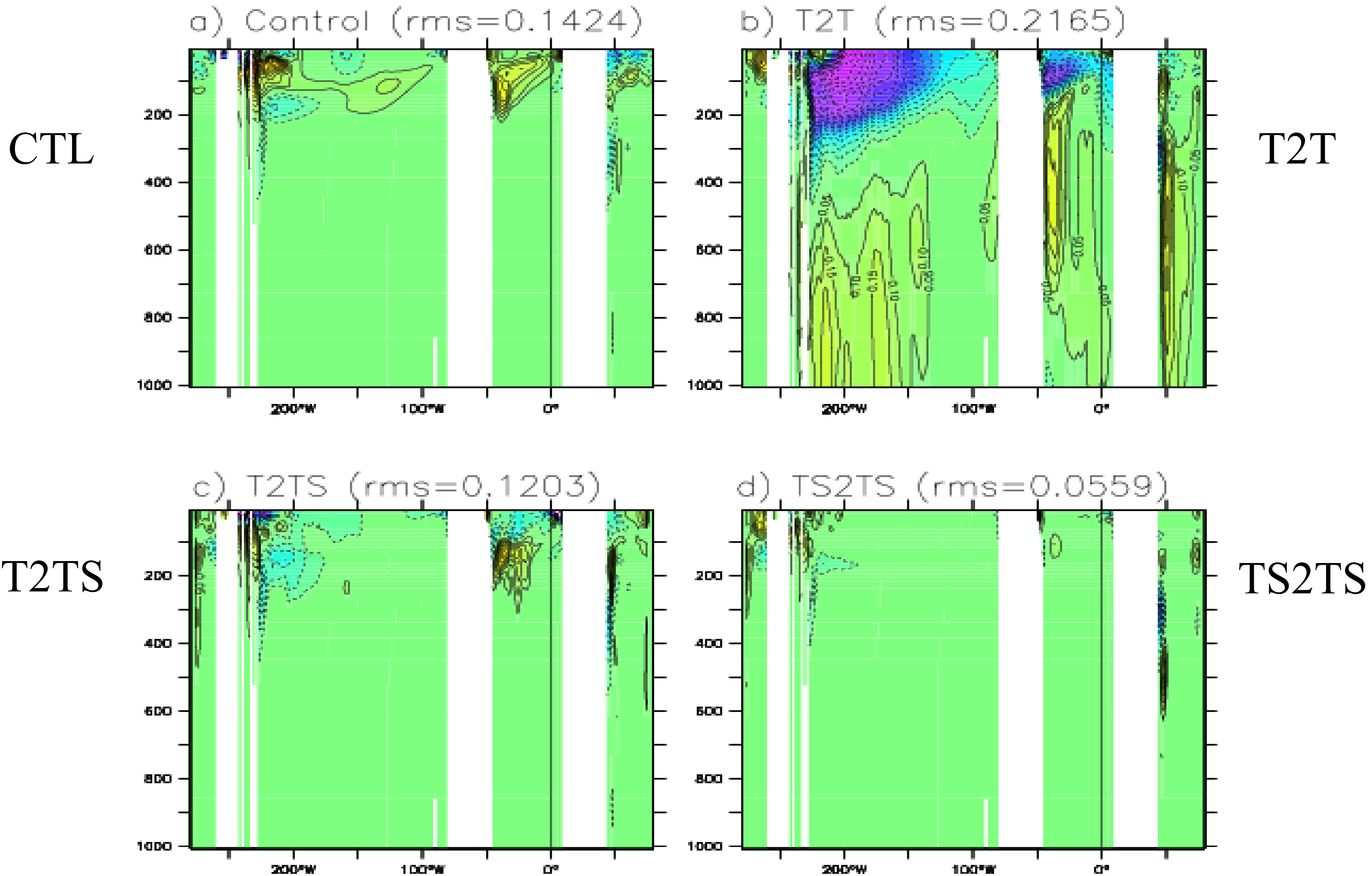
T2T

T2TS

TS2TS



Ocean salinity errors at the equator

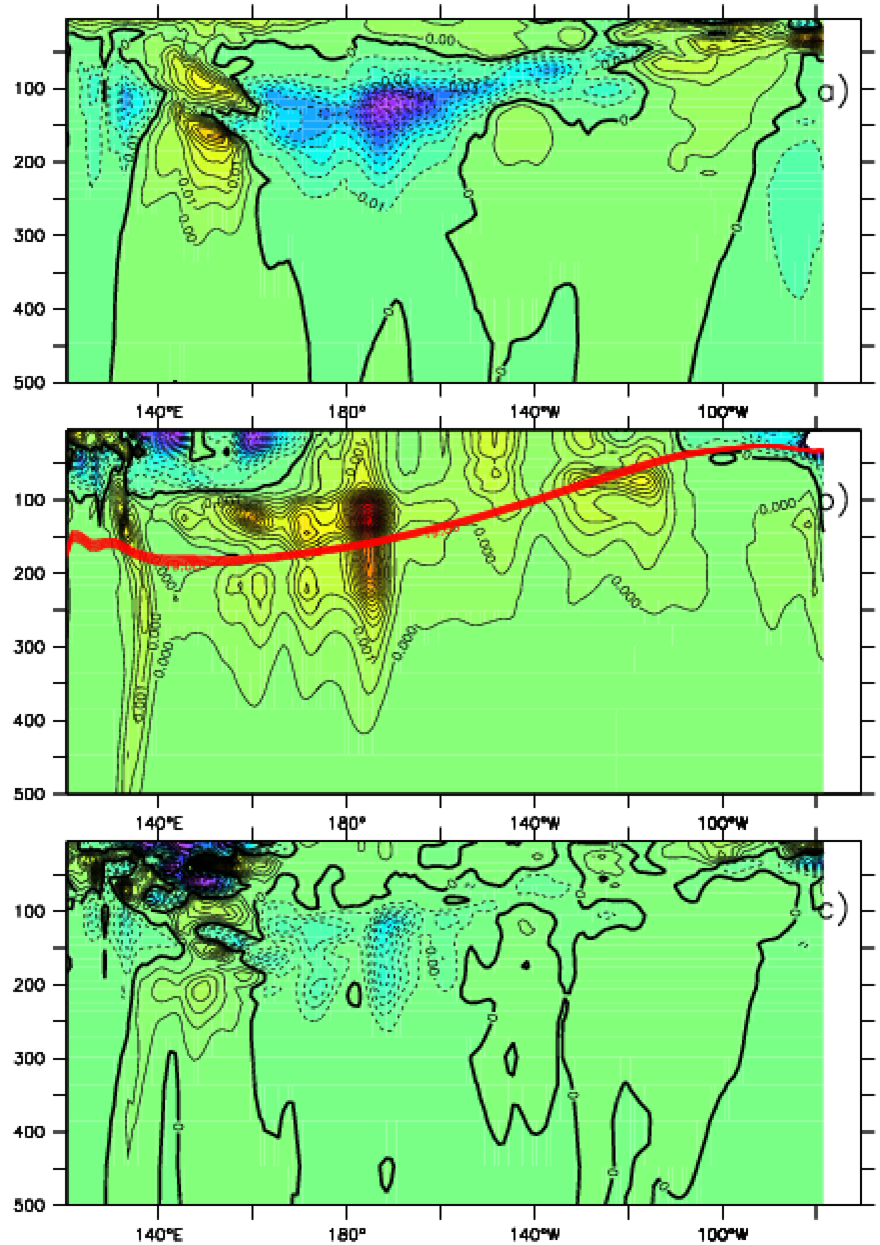


T, S corrections and T-S covariance at y=0 (1991 annual mean)

Temp correction

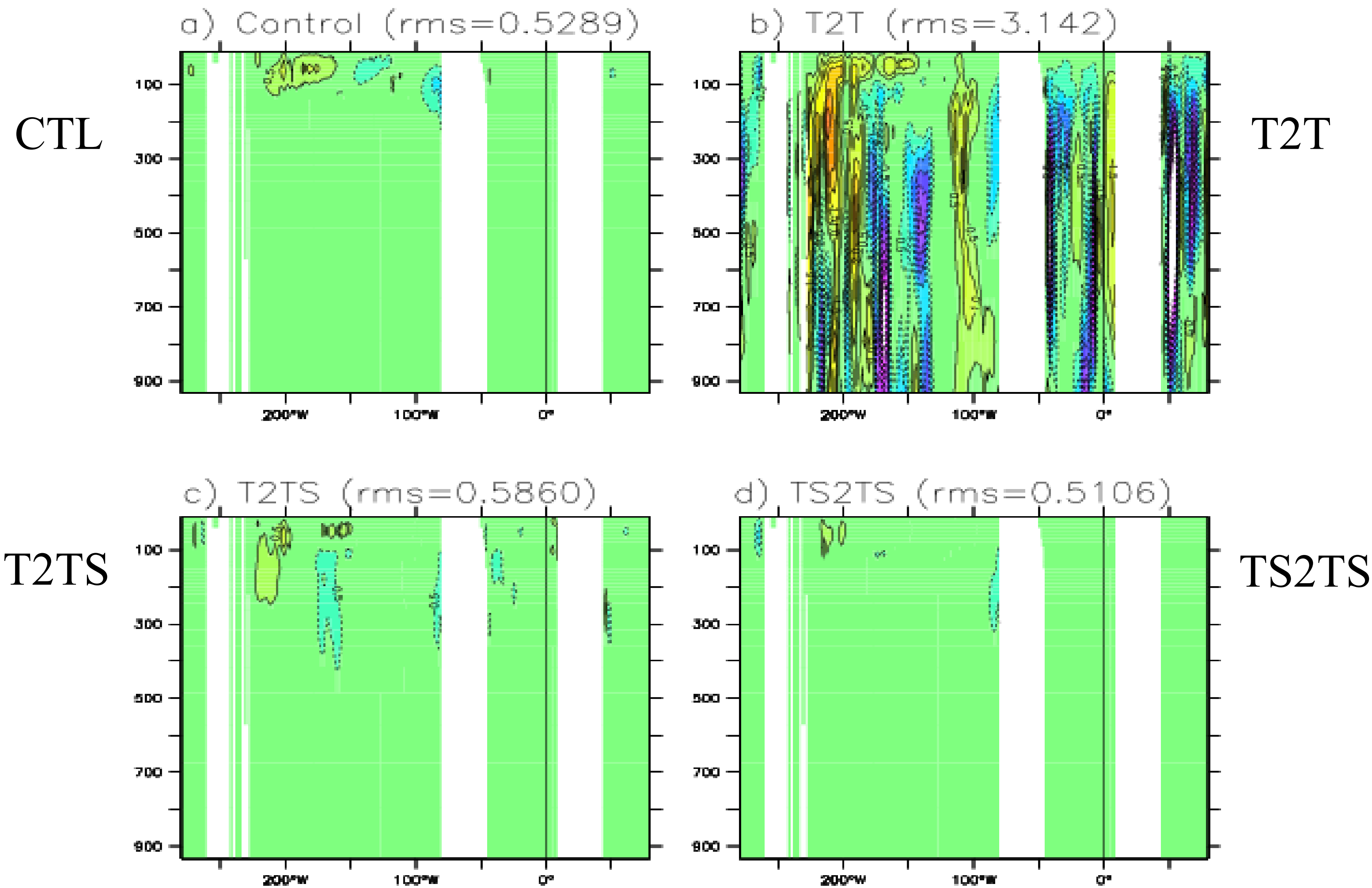
T-S covariance

Salinity correction

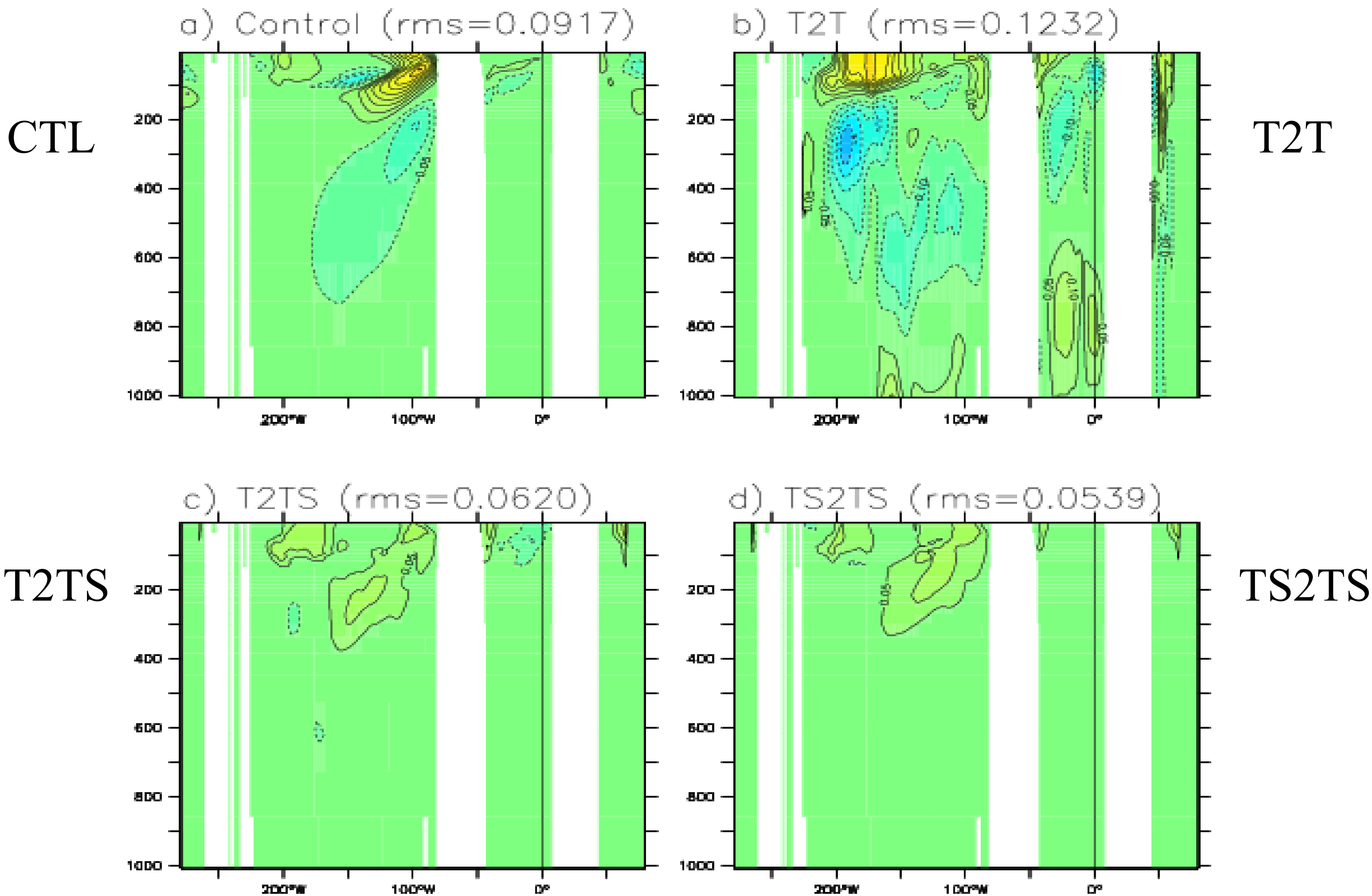


$$\Delta S = \frac{\mathrm{cov}(T,S)}{\delta_T^2}\Delta T$$

Vertical motion errors at the equator

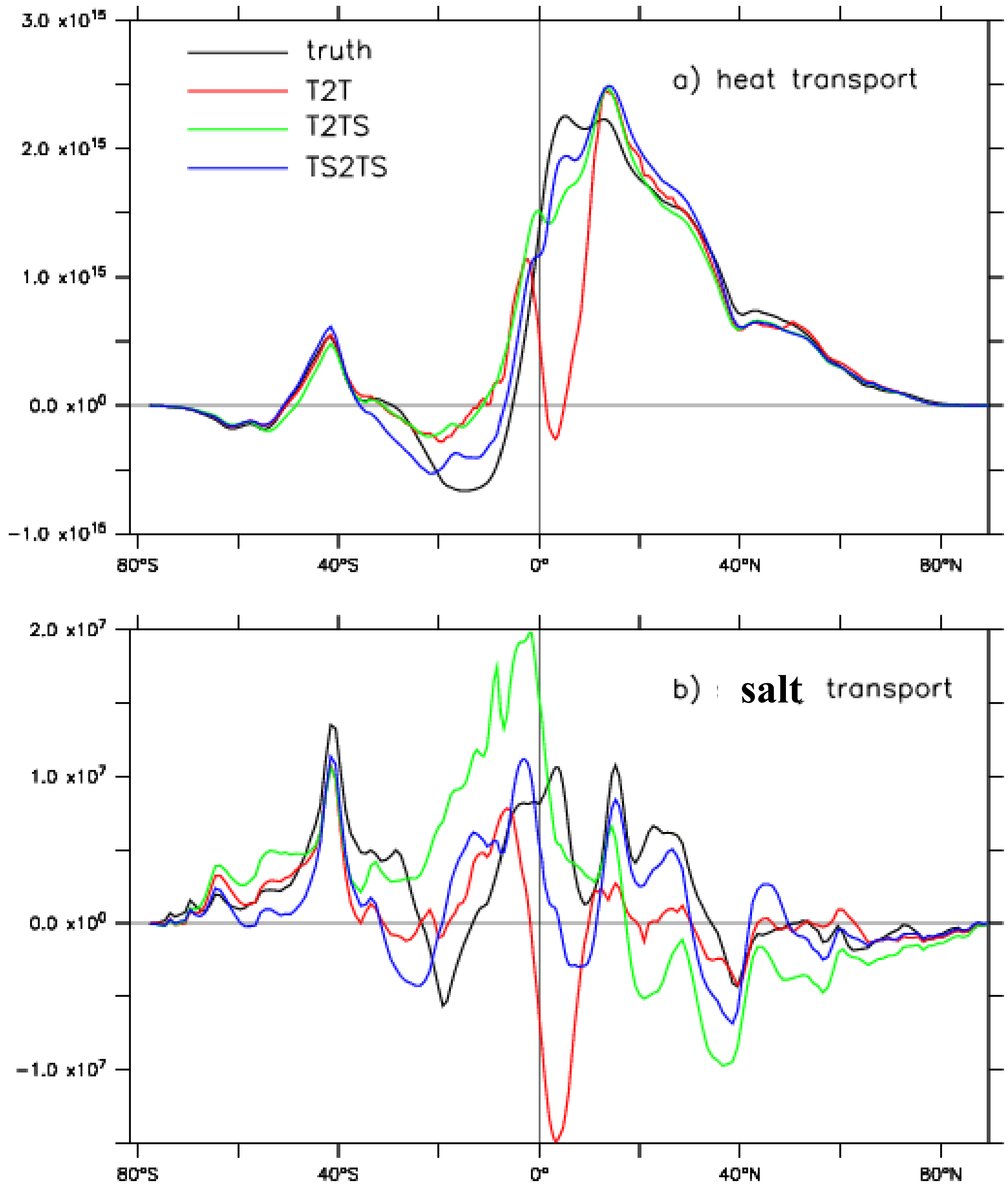


Under current errors at the equator



Integral of meridional heat/salinity transport in zonal-depth

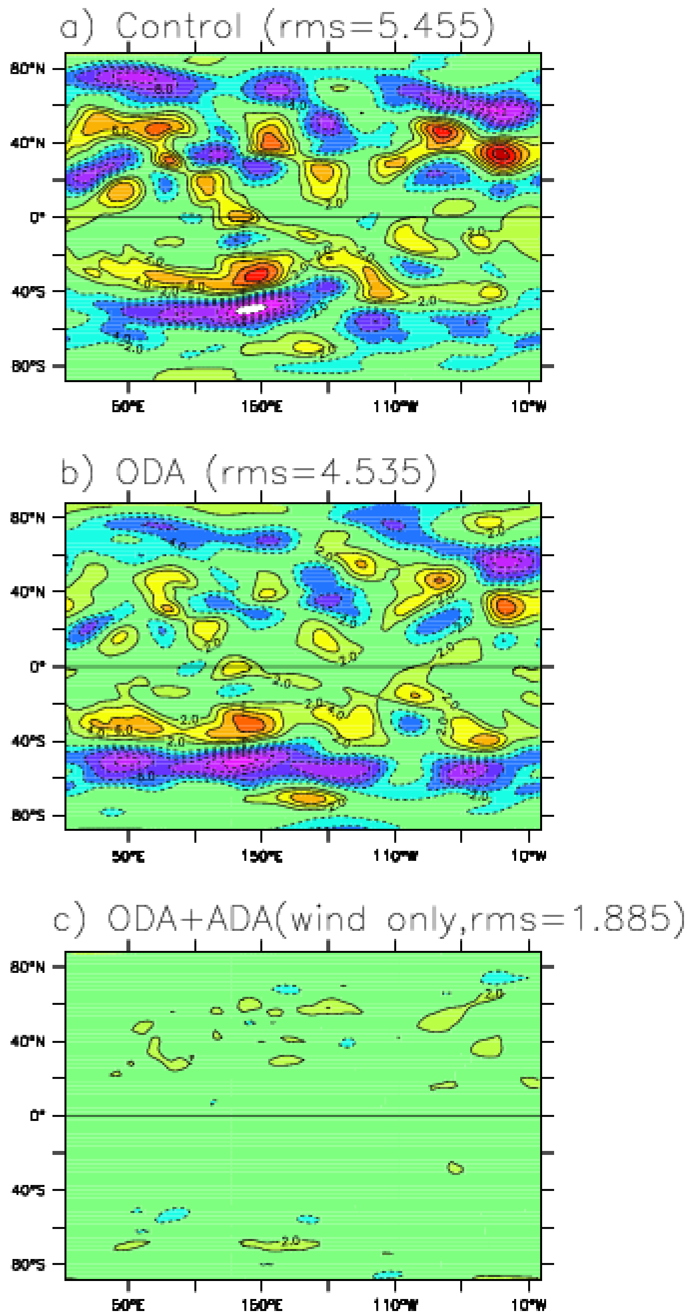
truth
t2t
t2ts
ts2ts



ADA Impact on Climate data assimilation:
Importance of maintaining geostrophic balance

- Monthly mean atmospheric data plus a white noise as obs
- Daily atmospheric analysis:
  - Assimilate winds only
  - Assimilating atmospheric temperature only
  - Assimilating atmospheric winds and temperature

Atmospheric Zonal Wind Errors (vertical average)

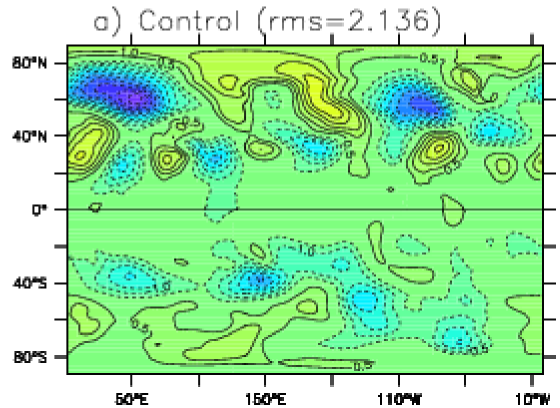


Control (without any data constraint)

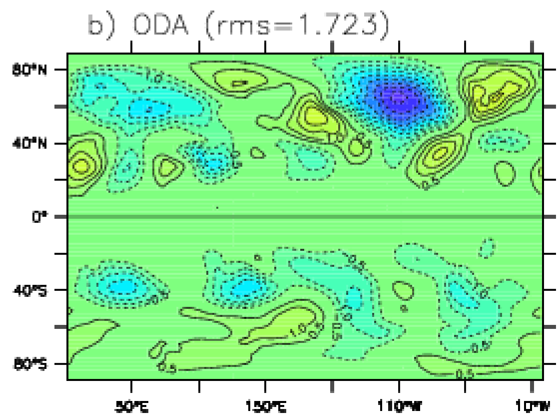
Ocean Data Assimilation (ODA) Only

ODA and Atmosphere Data Assimilation (ODA+ADA, wind only)

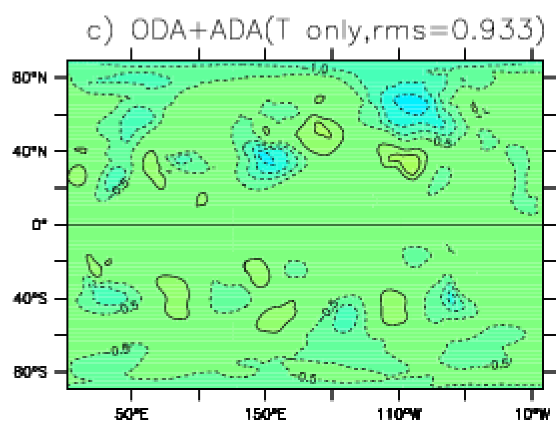
Atmospheric Temperature Errors (vertical average)



Control (without any data constraint)



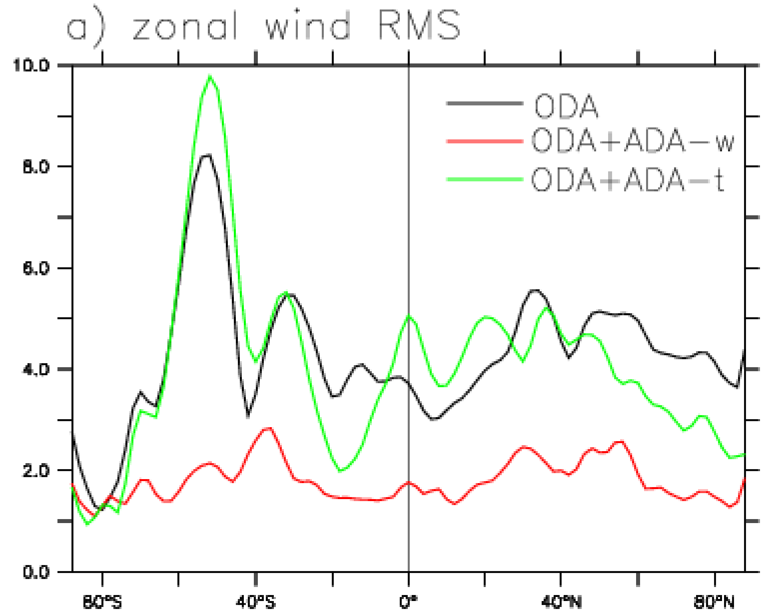
Ocean Data Assimilation (ODA) Only



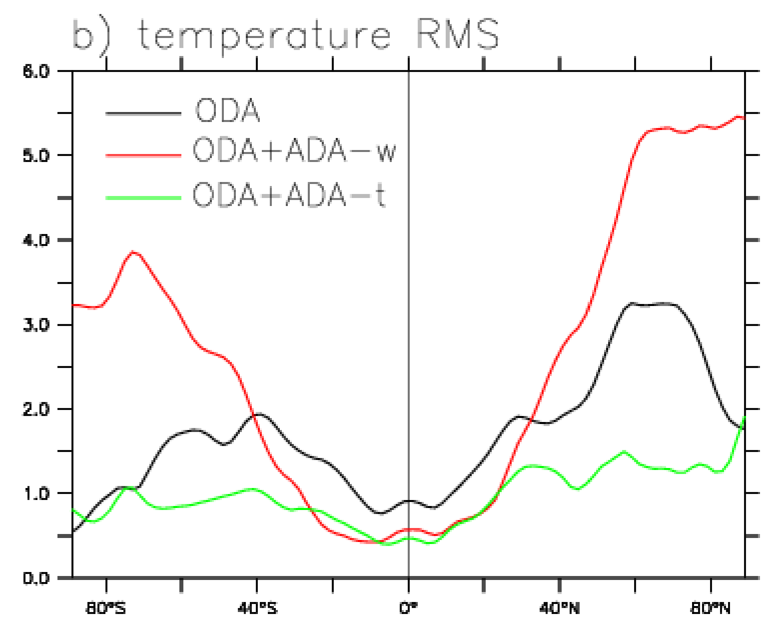
ODA and Atmosphere Data Assimilation (ODA+ADA, T only)

Atmospheric U & T rms errors

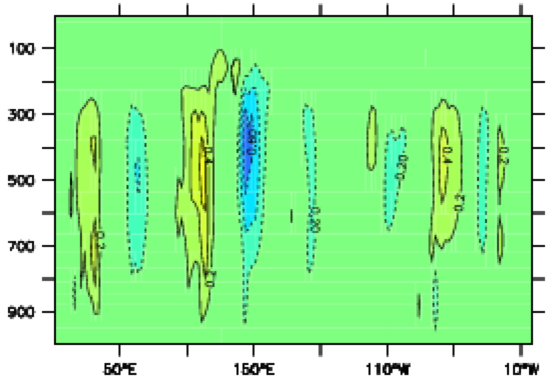
U rms



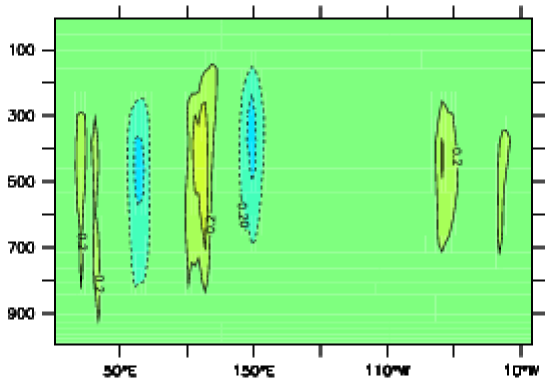
T rms



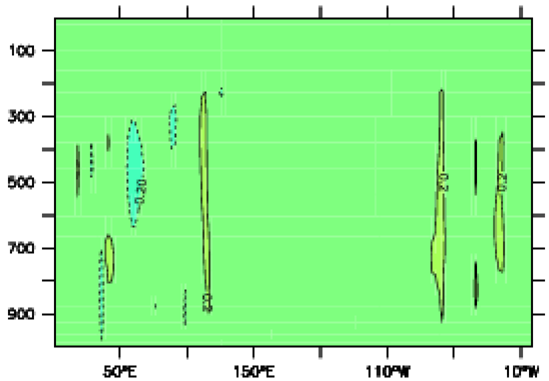
Atmosphere Vertical Motion (Walker Cell) Errors at Tropics (20^{o}S – 20^{o}N average)



Control (without any data constraint)

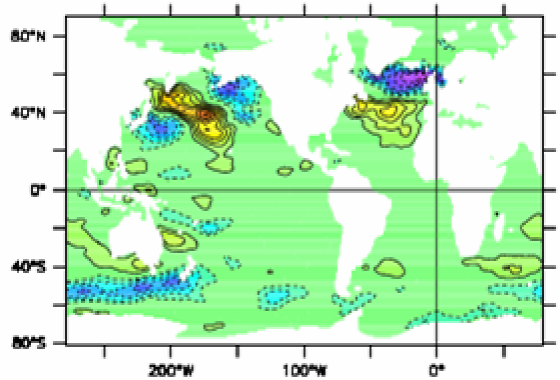


Ocean Data Assimilation (ODA) Only

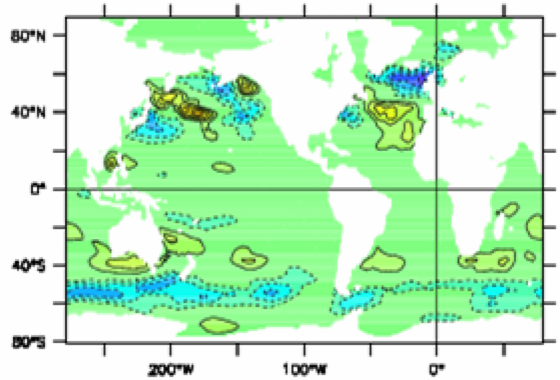


Ocean and Atmosphere Data Assimilation (ODA+ADA)

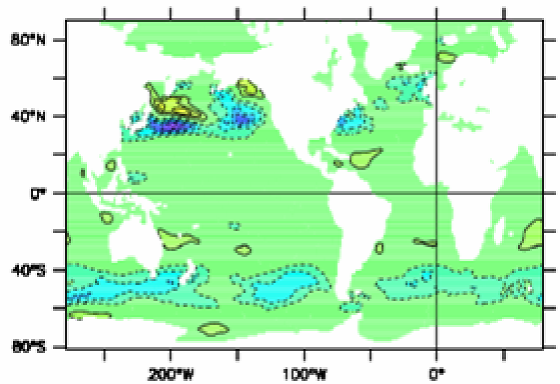
Zonal Wind Stress Errors at Ocean Surface Exerted by The Atmosphere Bottom



Control (without any data constraint)



Ocean Data Assimilation (ODA) Only



Ocean and Atmosphere Data Assimilation
(ODA+ADA)

Summary on CDA tests:

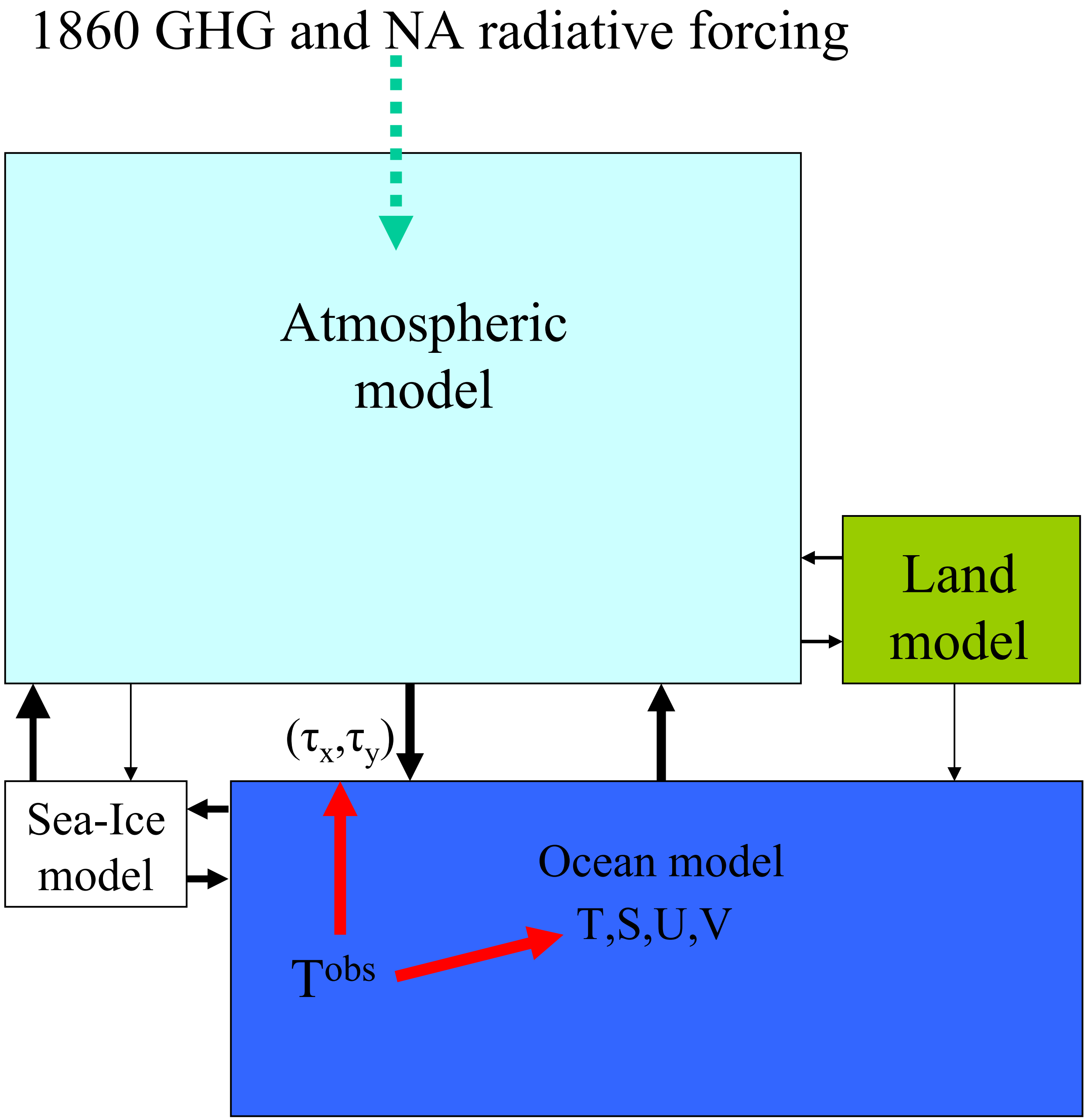
Accessing Climate Changes Using Coupled Model & Data Solves a Temporally-Evolving *Joint-Distribution* of Climate State Variables

- ✓ Estimating a temporally-evolving ***joint-distribution*** requires:
  - – Multi-variate analysis scheme maintains physical balances among state variable
    - T-S relationship in ODA
    - Geostrophic balance in ADA
  - – Adjustment ensemble filter maintains the properties of high order moments of error statistics (nonlinear evolution of errors) mostly
- ✓ An adjustment ensemble filter maintains the above two properties as much as possible

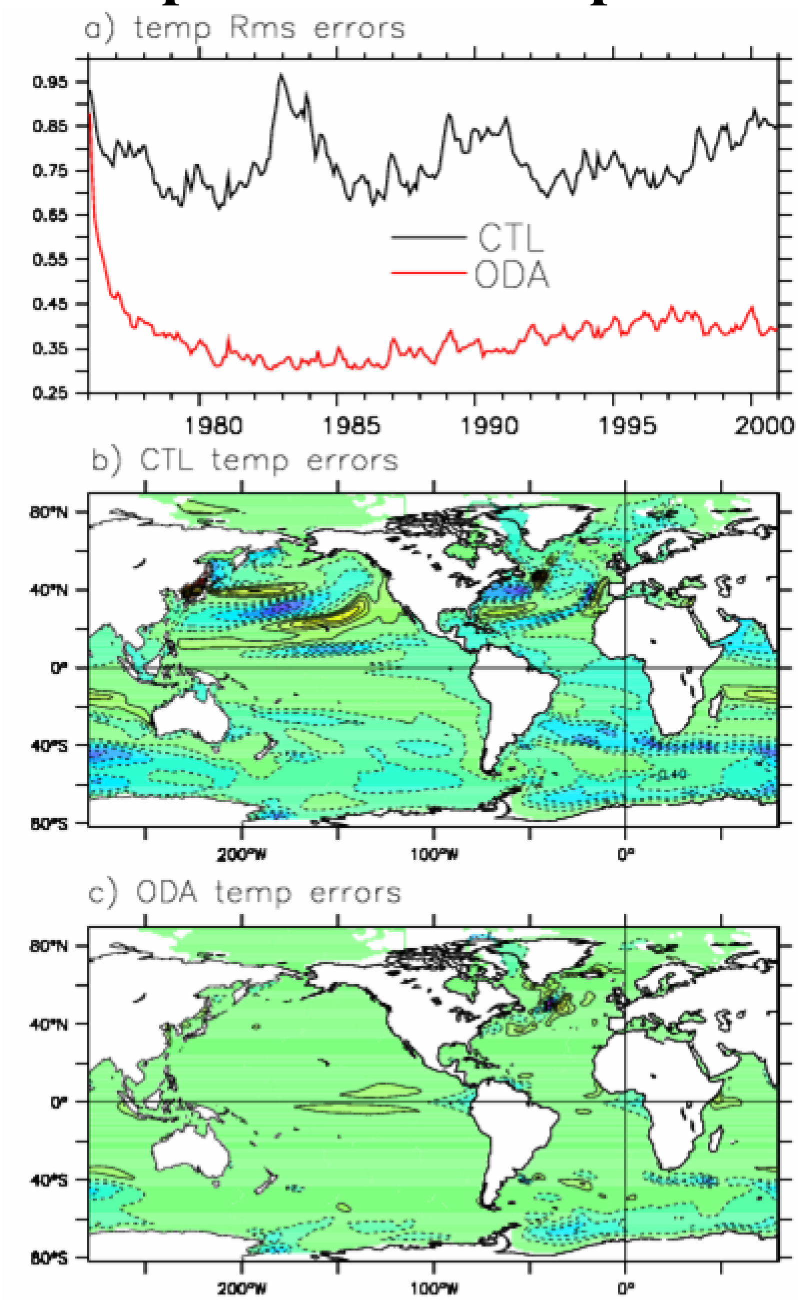
Climate change detection for the last quarter of 20th century?

- ✓ Idealized twin experiments:
  - Truth: 20th Century climate simulation forced by time-varying green-house-gas radiation (IPCC historical run)
  - Observations: Projecting the IPCC historical run temperature onto 20th century ocean temperature observational network (XBT, CDT, MBT, OSD, …), plus an N(0,0.5) white noise
- ✓ Assimilation Model: CM2 control run – Fixed-year (1860) **GHGNA forcing**
  - B-grid atmospheric model, 144x90x24 and Land model (LM2.0)
  - Version 4 of module ocean model (MOM4), 360x200x50 and Sea Ice Simulator (SIS)
- ✓ Initialize the model from arbitrary initial conditions (75 years ago, for instance)

Question: How much can we retrieve signals of climate change, both variability and trend, given the 20th century temperature observational network?


1860 GHG and NA radiative forcing
Atmospheric model
Land model
(τ_x,τ_y)
Sea-Ice model
Ocean model
T,S,U,V
T^{obs}

Temp errors over top 500m



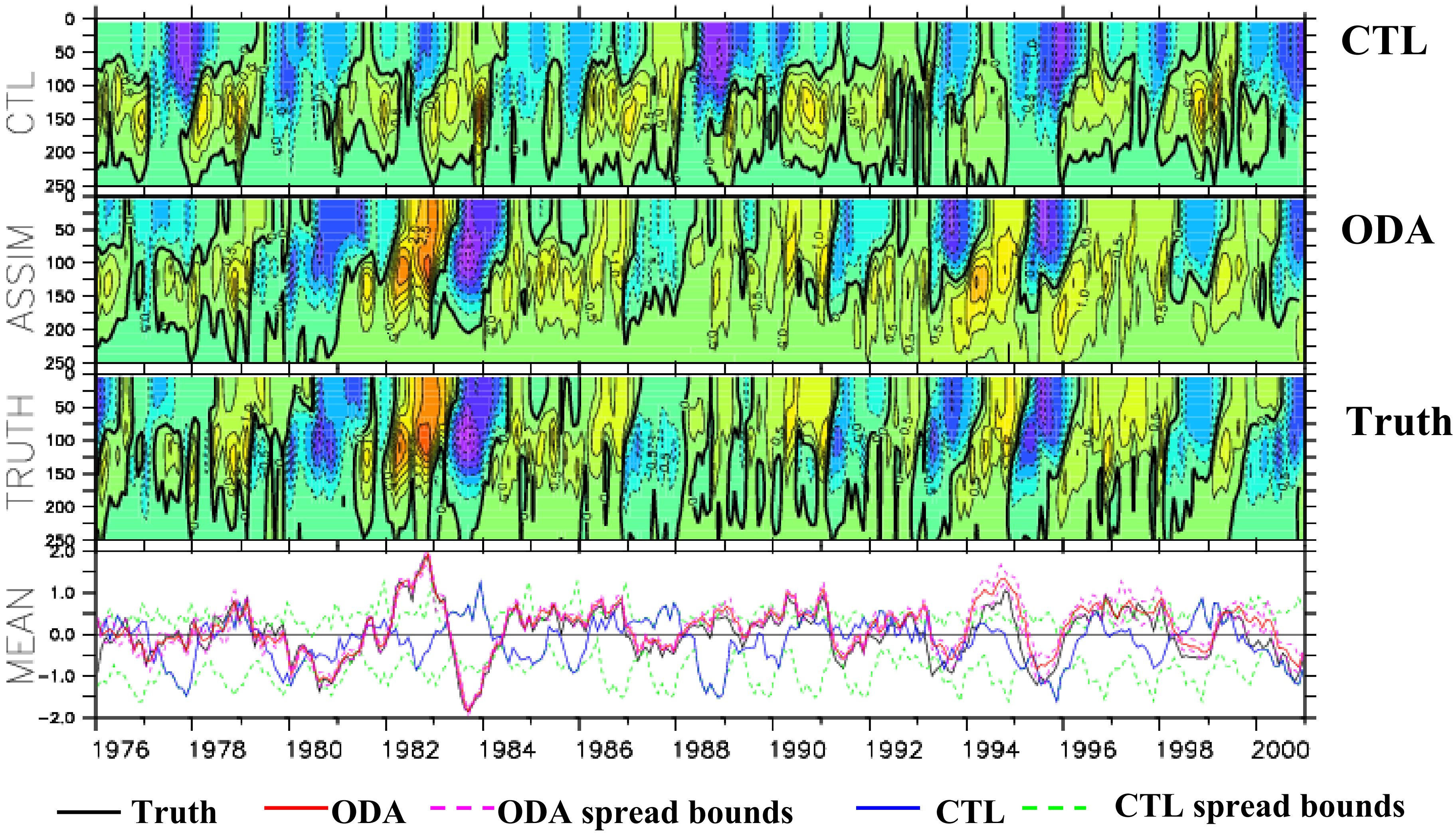
Global Rms error

CTL Averaged errors

ODA Averaged errors

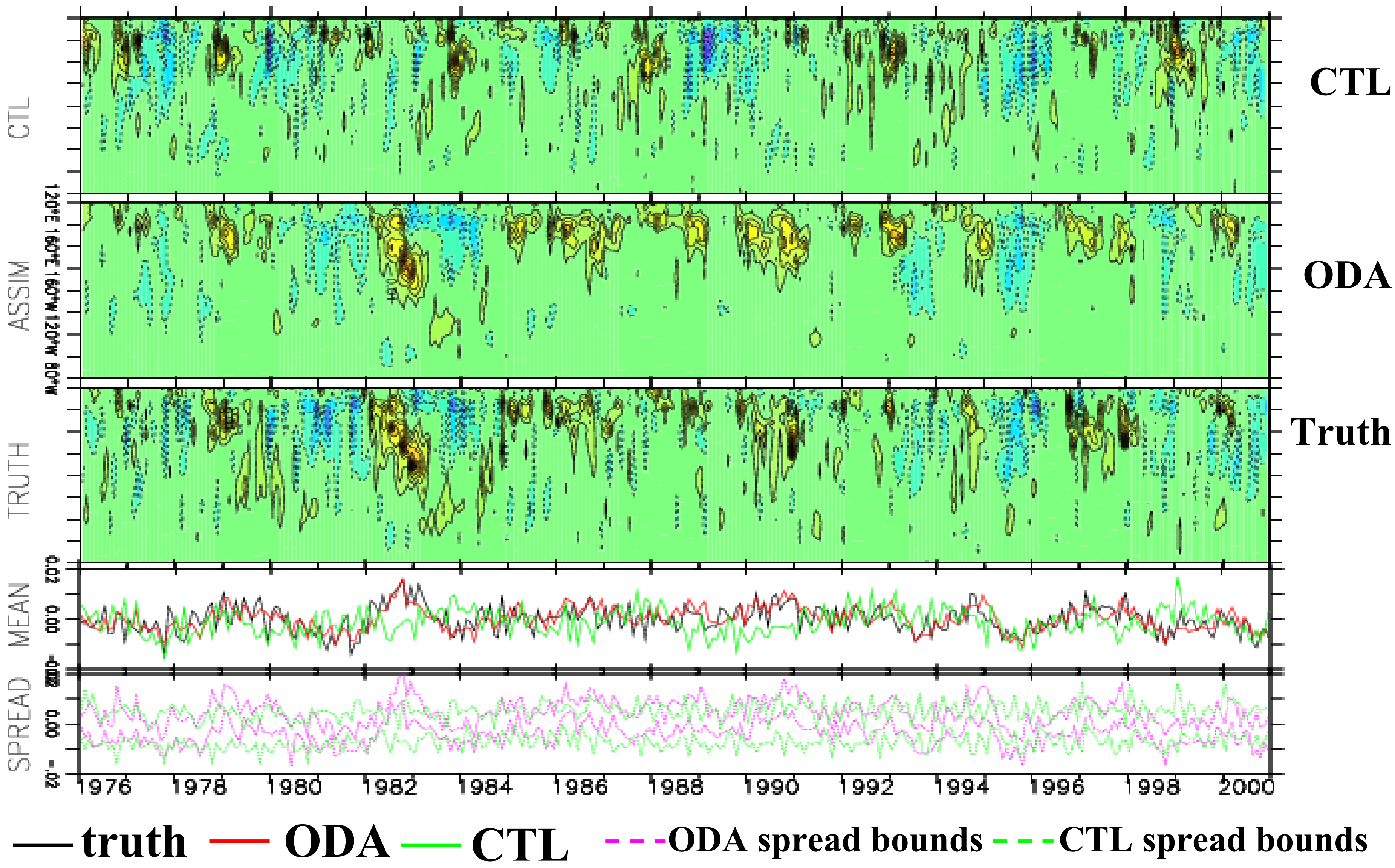
25yr climate detection: ENSO variability

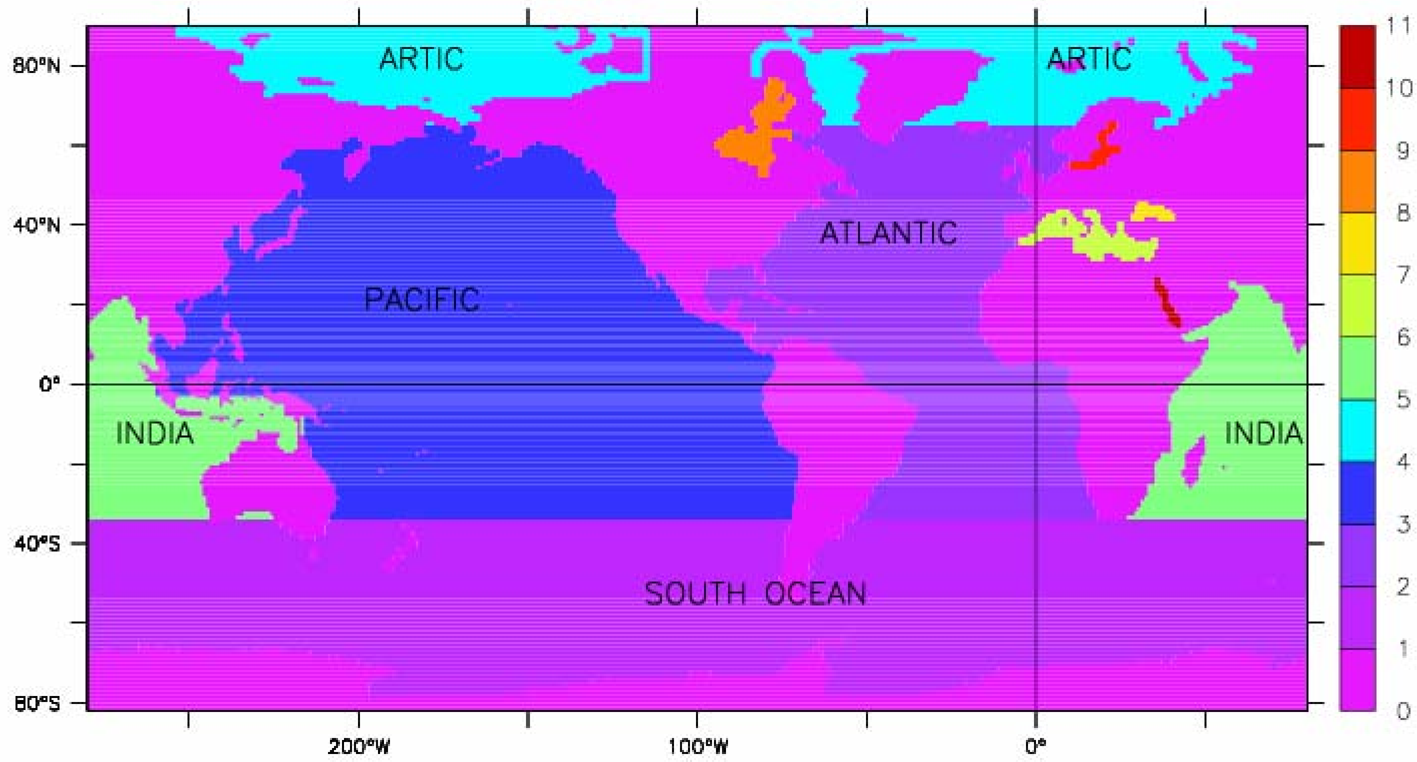
1) Temperature at NINO3.4



25yr climate detection: ENSO variability

2) Zonal wind stress (τ_x) at tropical Pacific (5S-5N average)

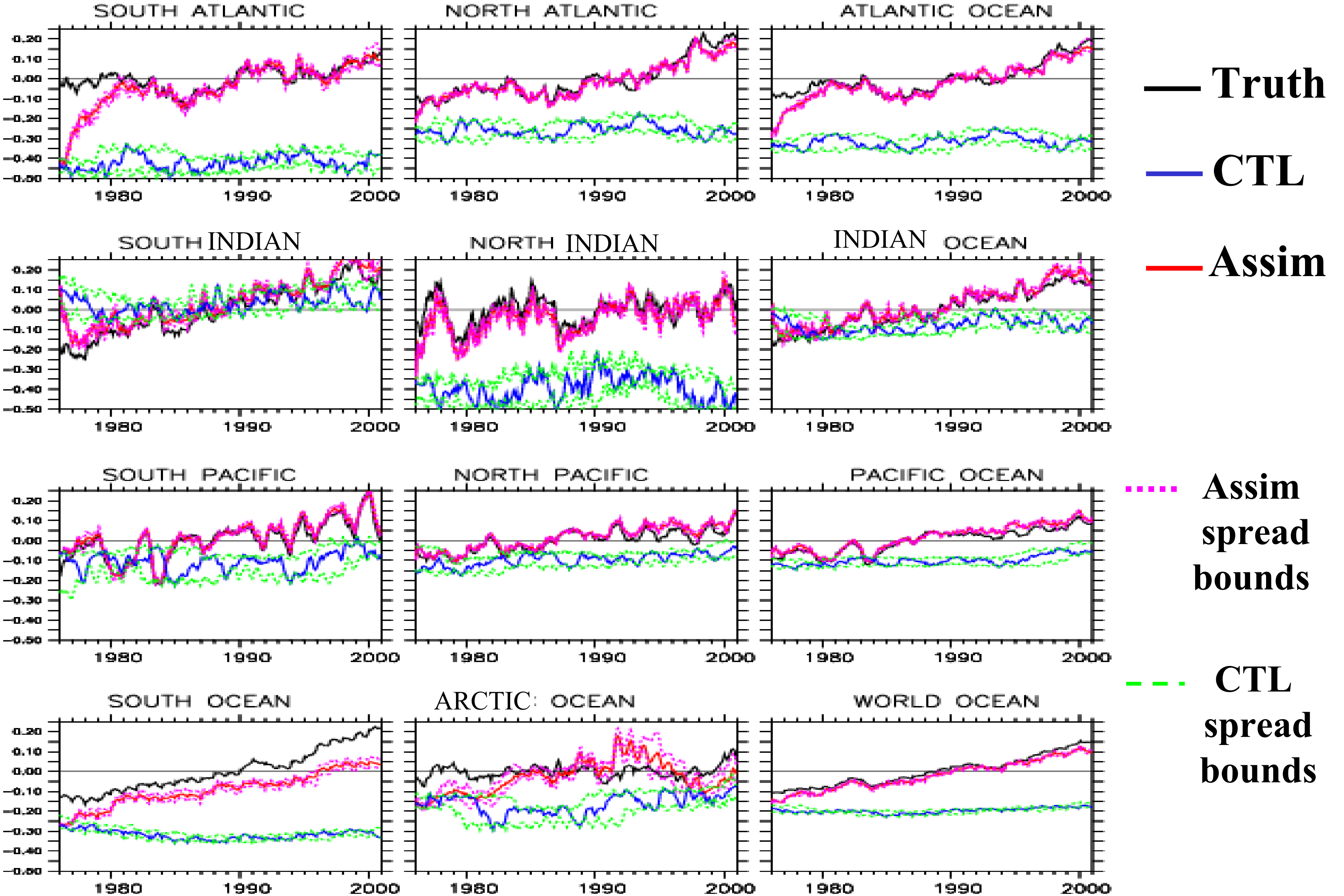




ARTIC
ARTIC
ATLANTIC
PACIFIC
INDIA
INDIA
SOUTH OCEAN
80°N
40°N
0°
40°S
80°S
200°W
100°W
0°
11
10
9
8
7
6
5
4
3
2
1
0

How much can we retrieve the trend of climate change?

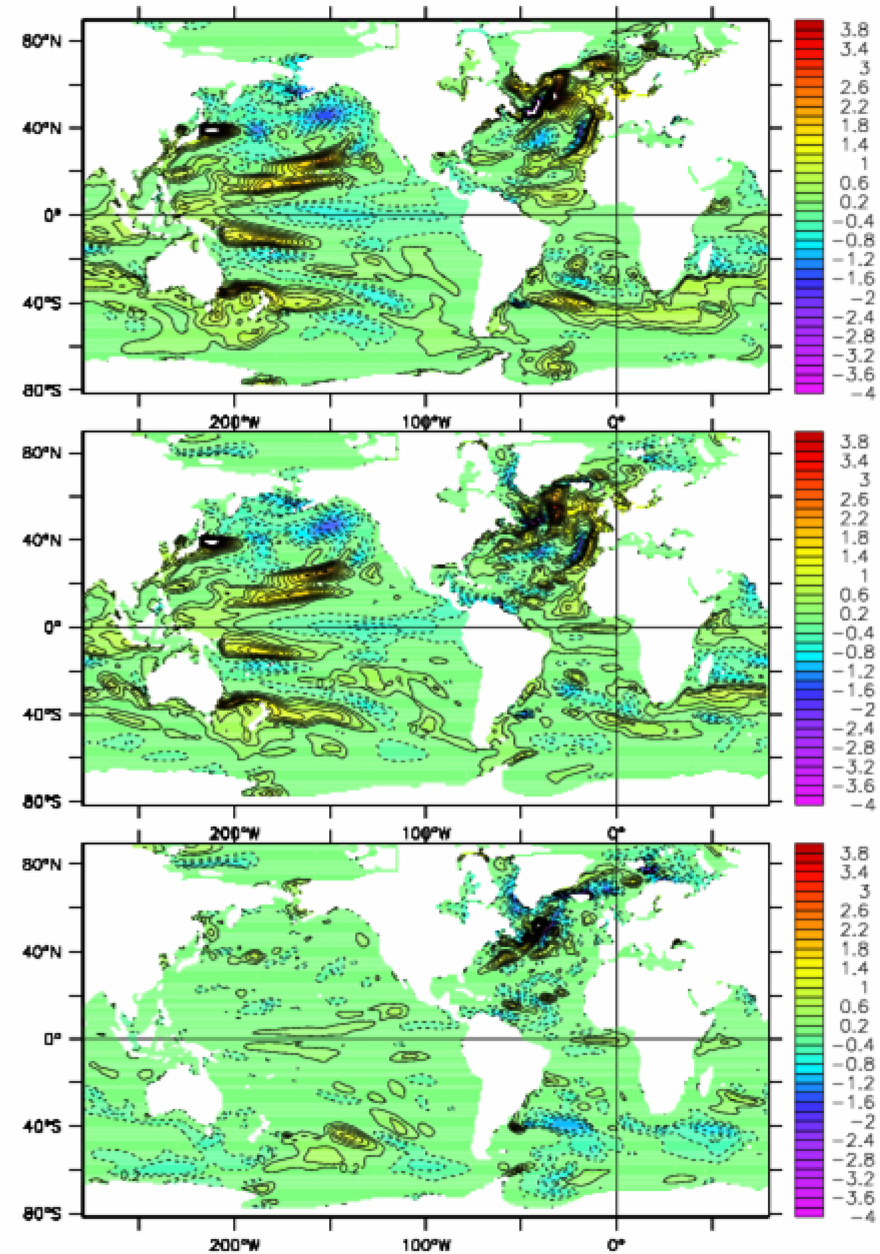
1) Top 500 m Ocean Heat Content (Averaged Temperature) Anomalies



How much can we retrieve the trend of climate change?

2) Top 500 m ocean heat content 10yr tendency (2000 – 1990)

Contour interval = 0.2 ^{o}C



Truth

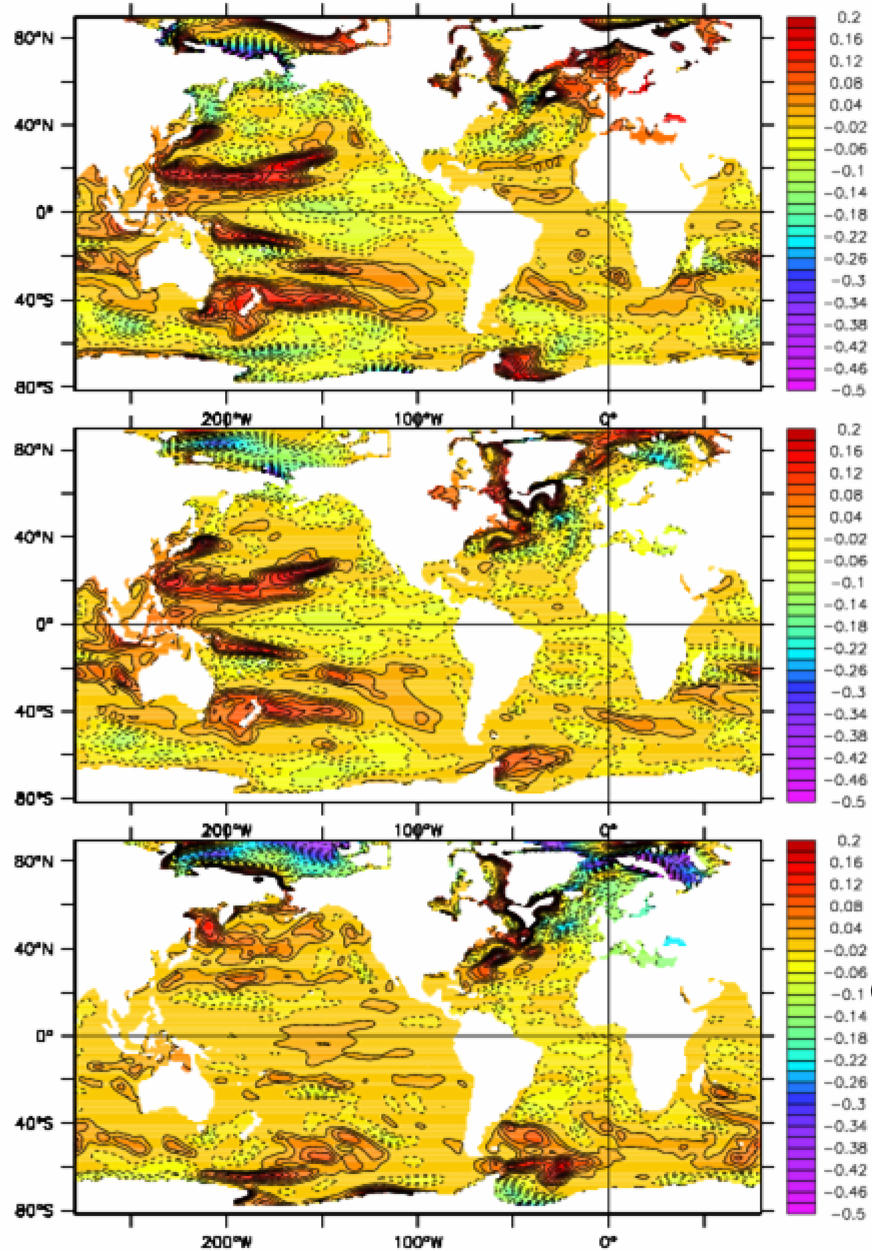
ODA

ODA - Truth

How much can we retrieve the trend of climate change?

3) Sea surface height
10yr tendency
(2000 – 1990)

Contour interval
= 0.02 (m)

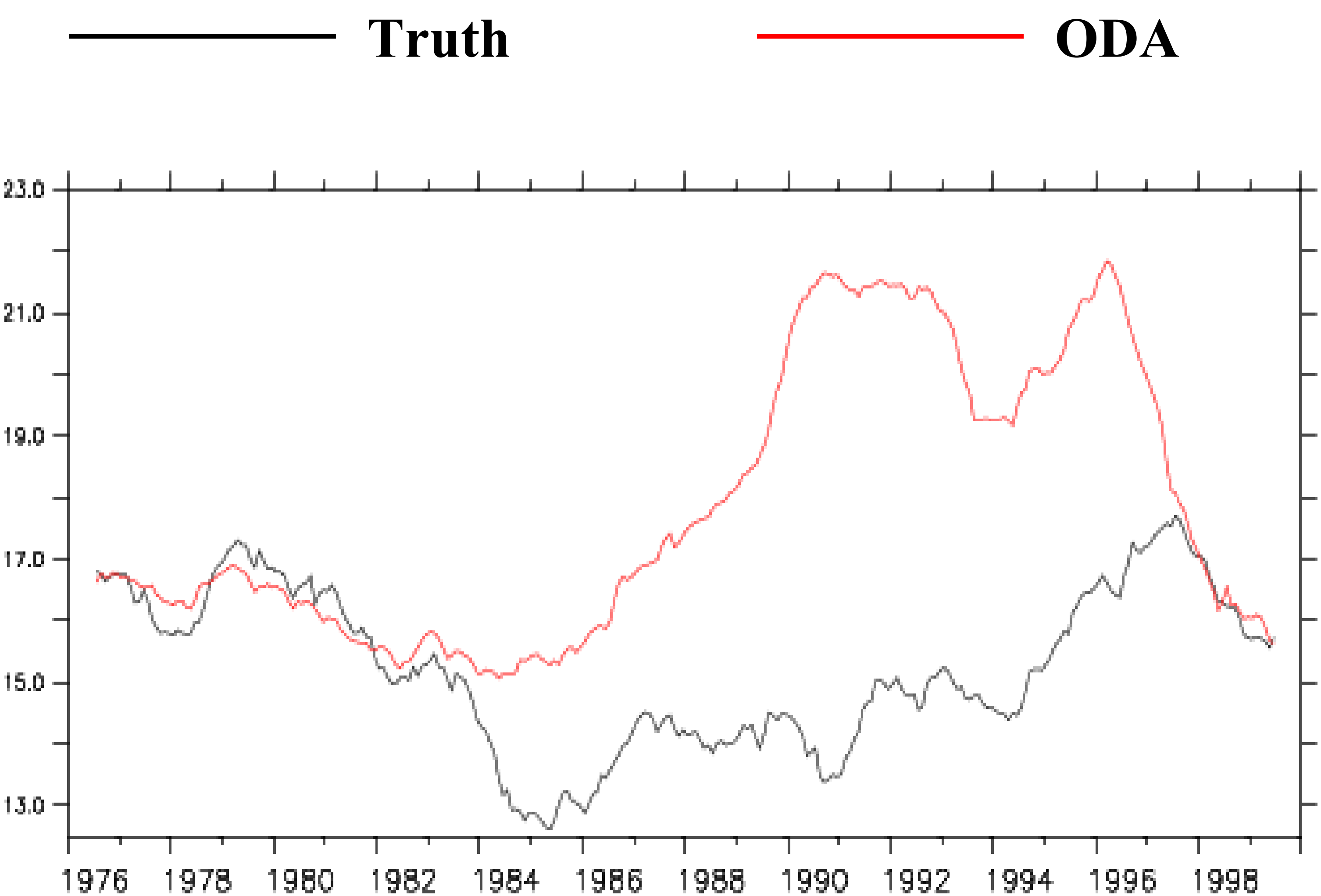


Truth

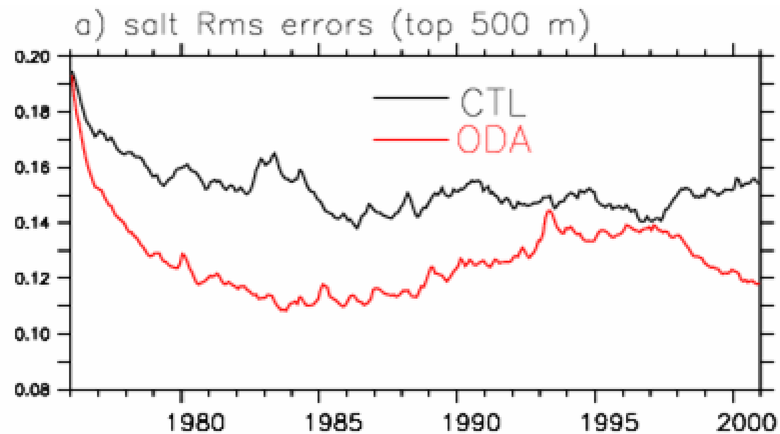
ODA

ODA - Truth

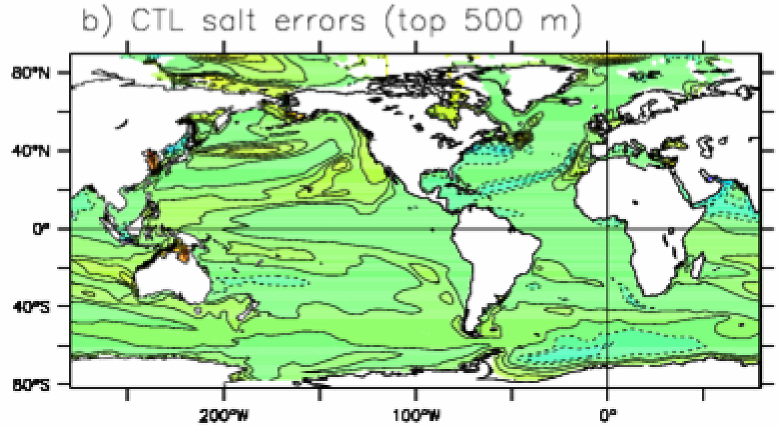
Challenges:
1) North Atlantic Meridional Overturning



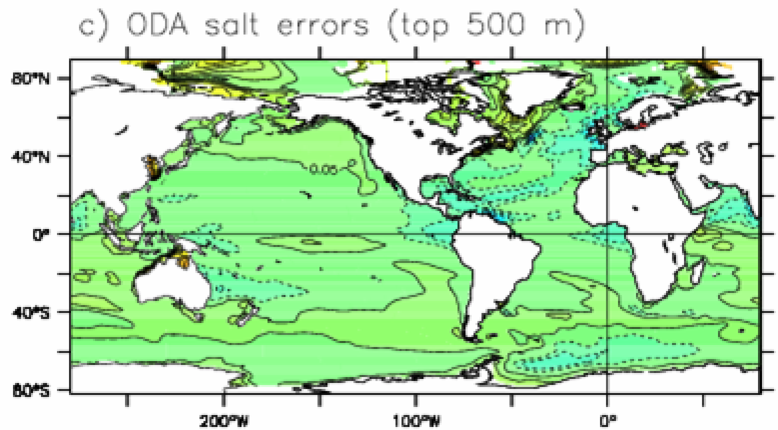
2) Salinity errors over top 500m



Global Rms error

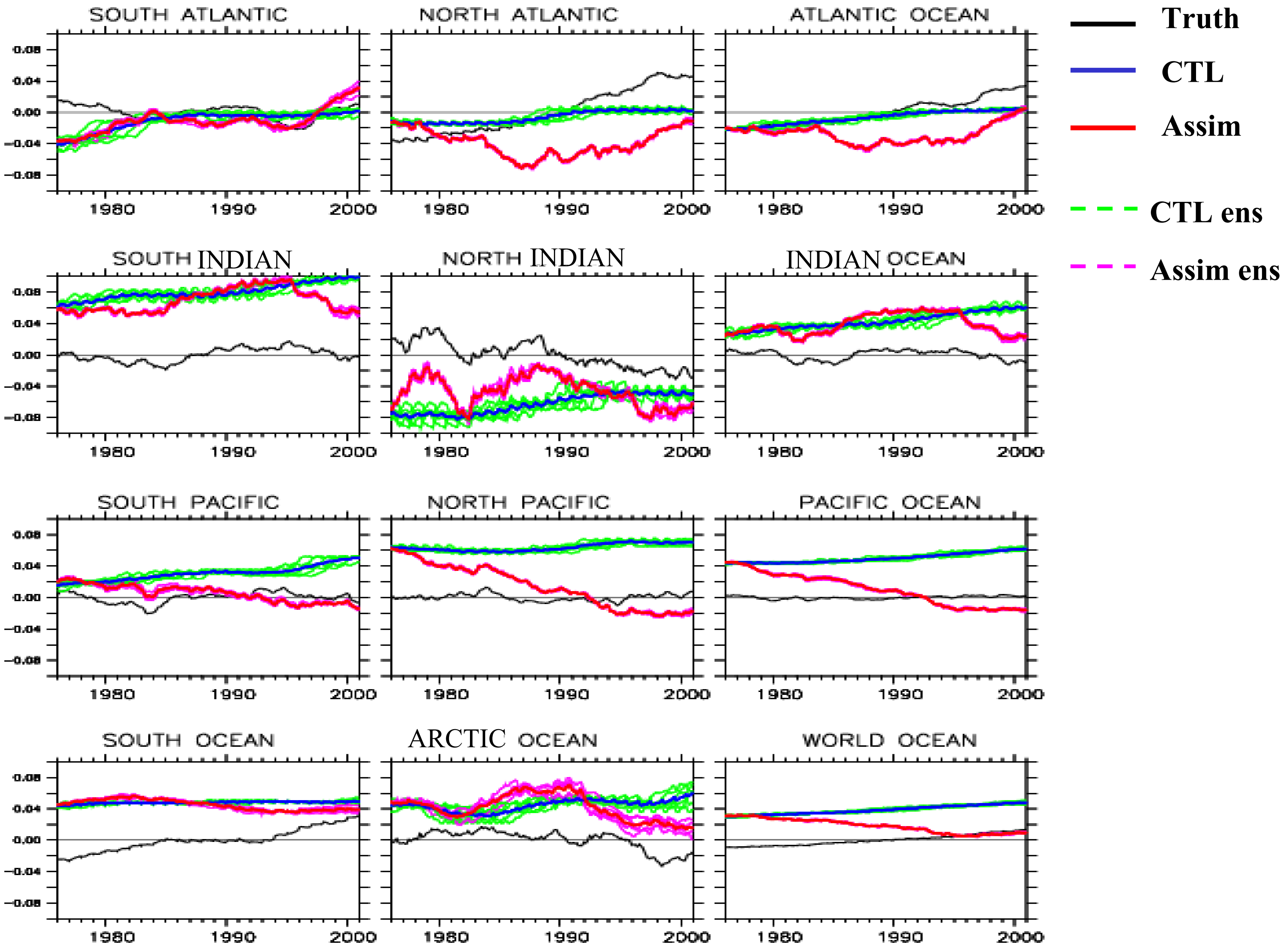


CTL Averaged errors



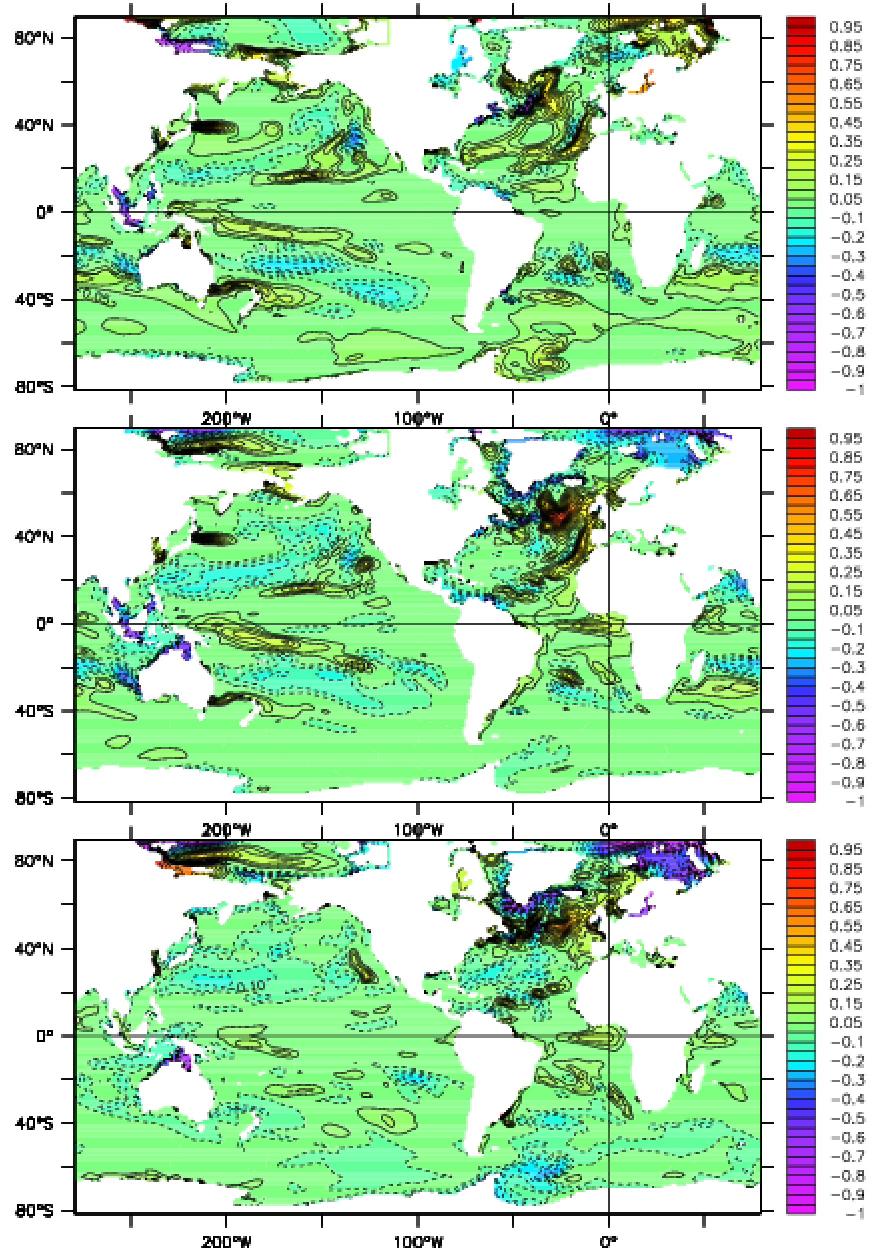
ODA Averaged errors

Challenge: 2) Top 500 m Salt Anomalies



Challenge: 3) Salt 10yr tendency (2000-1990)

Contour interval = 0.05 (PSU)

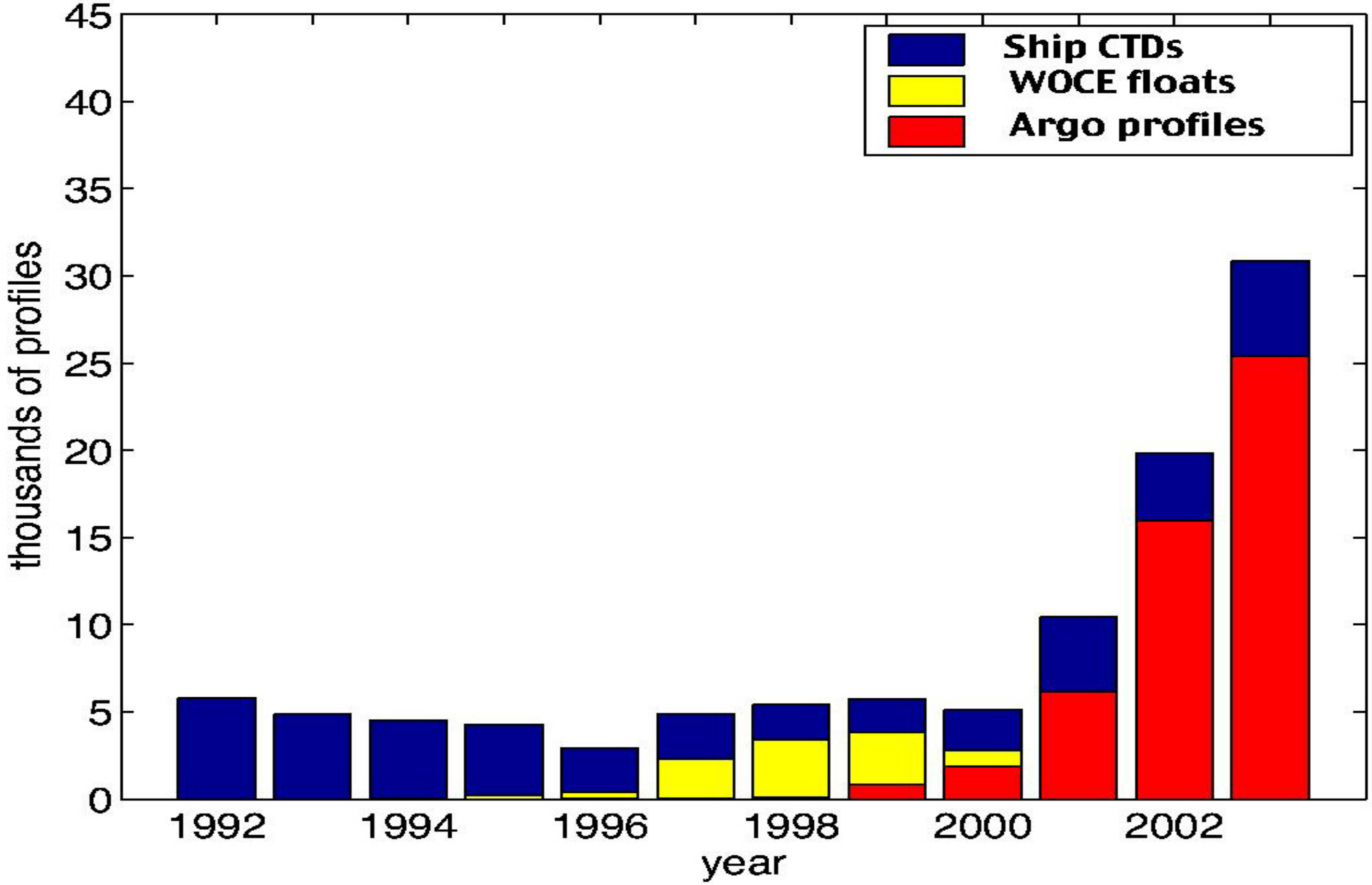


Truth

ODA

ODA - Truth

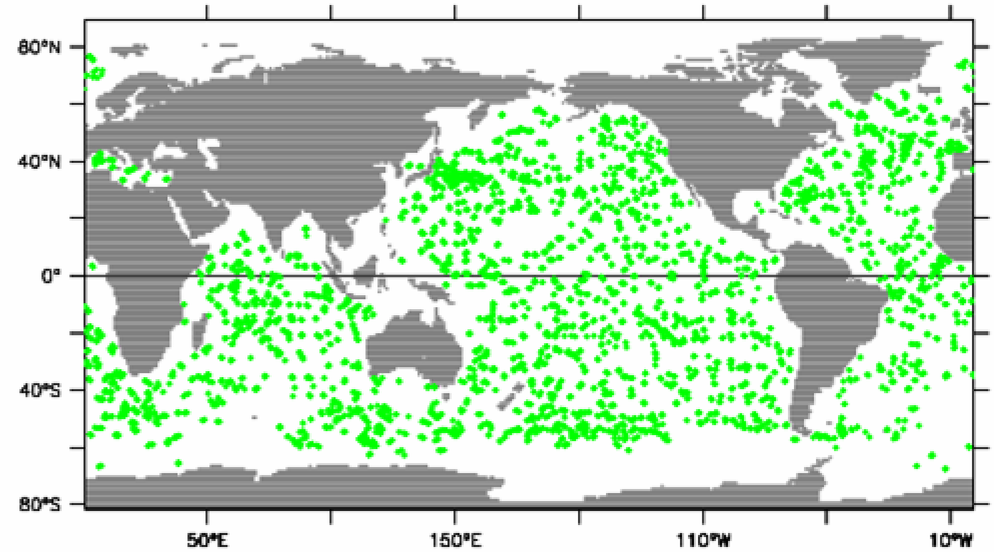
Argo and the Salinity Budget



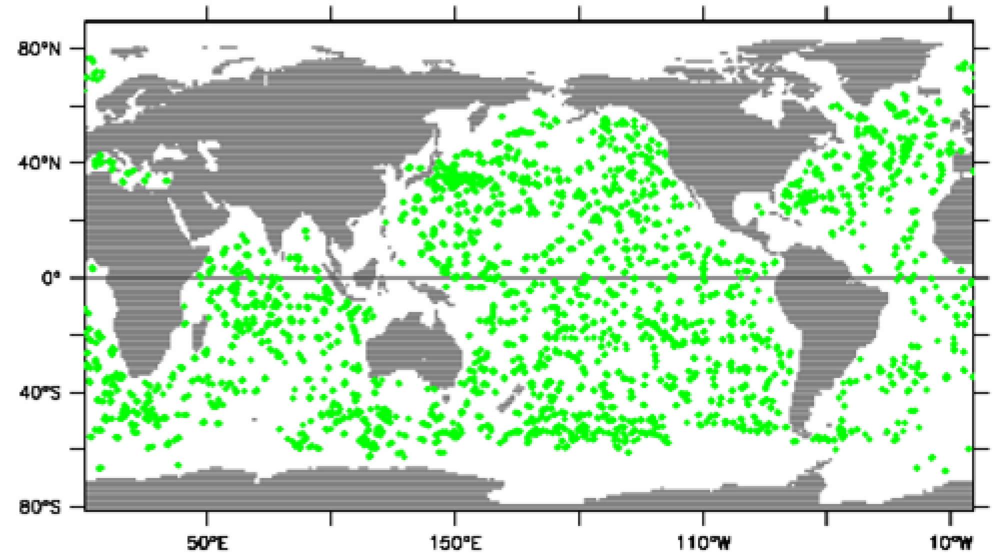
Historical Salinity Profiles

2005 June Argo network

Temperature



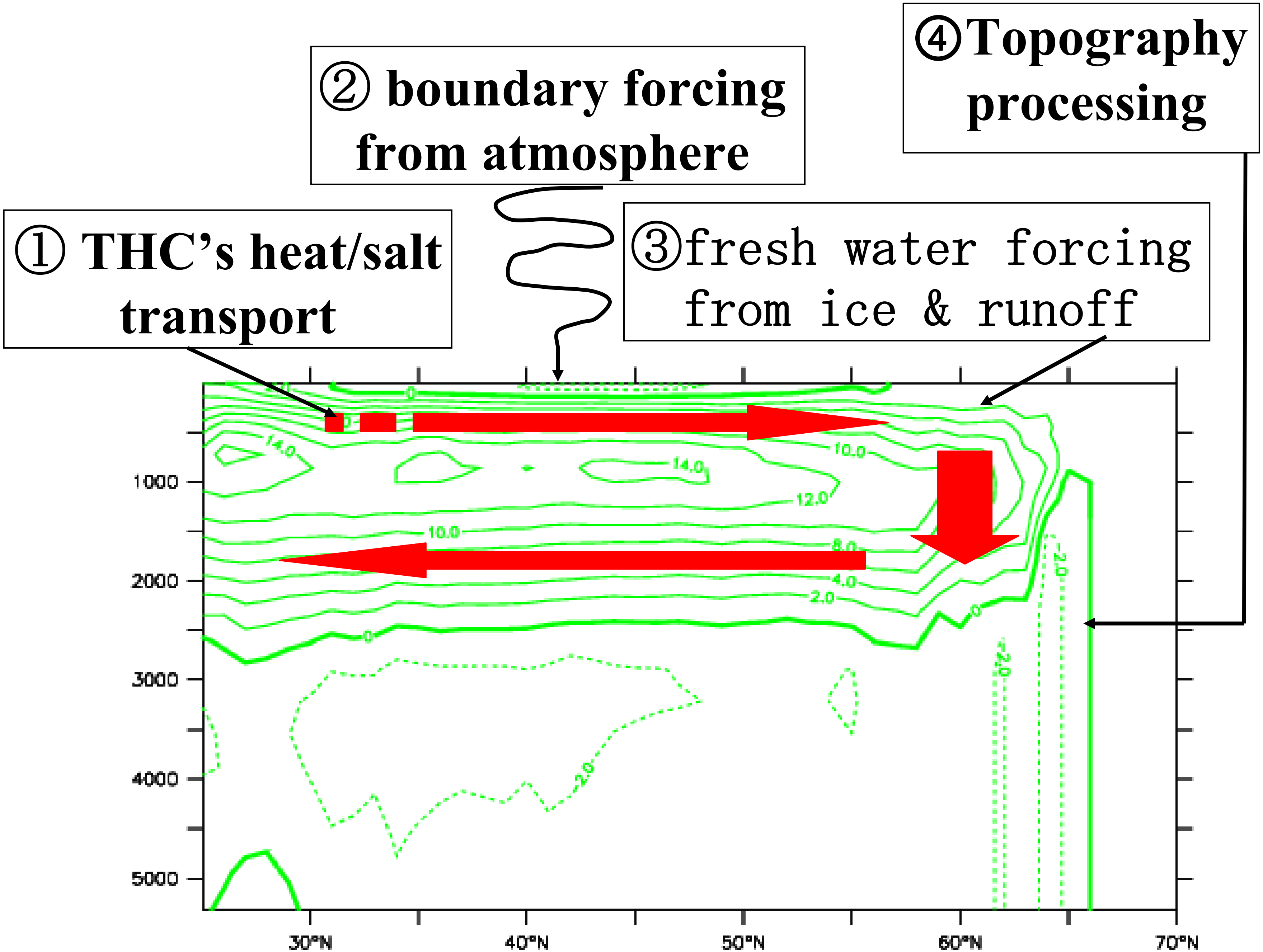
Salinity



Estimate of Atlantic Meridional Overturning Circulation (MOC)

✓Based on 2005 Argo network:

- Only using top 500 m ocean temperature measurements
- Only using top 500 m ocean temperature and salinity measurements
- Using Argo measurements (down to 2000 m deep for temperature and salinity)

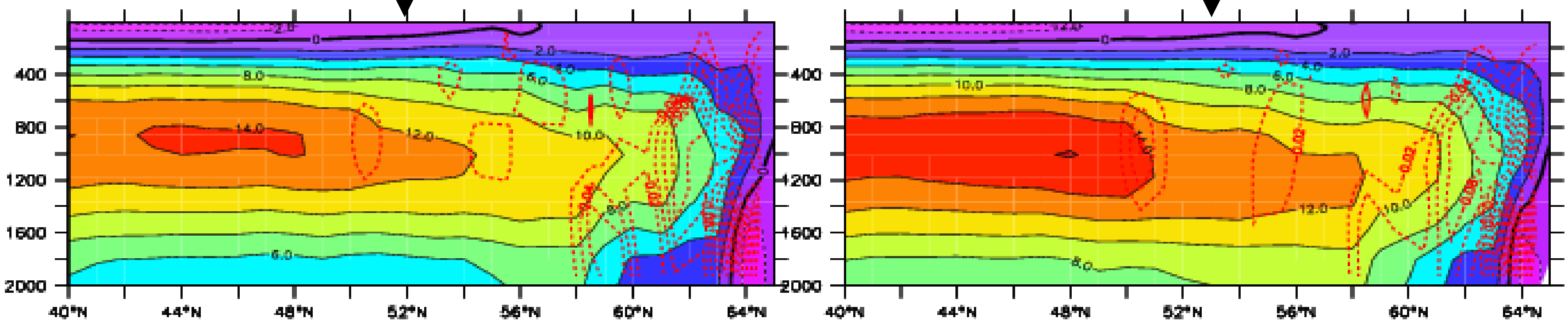


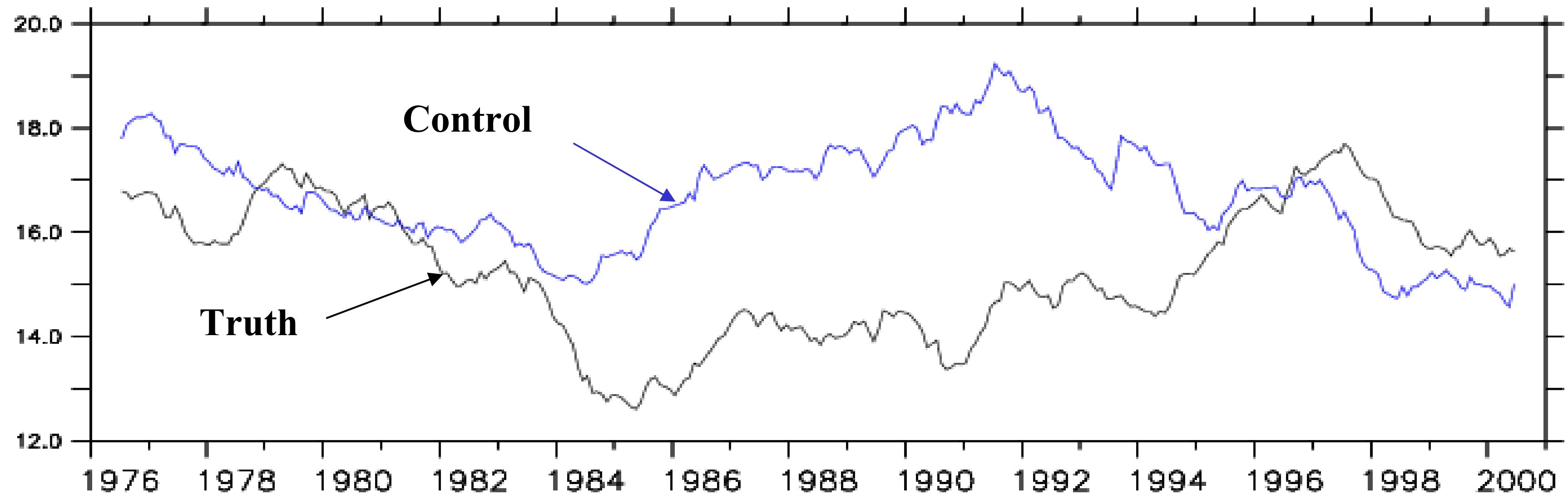
② boundary forcing from atmosphere
④Topography processing
① THC's heat/salt transport
③fresh water forcing from ice & runoff
14.0
10.0
14.0
12.0
10.0
8.0
4.0
2.0
0
0
-2.0
-2.0
-2.0
1000
2000
3000
4000
5000
30°N
40°N
50°N
60°N
70°N

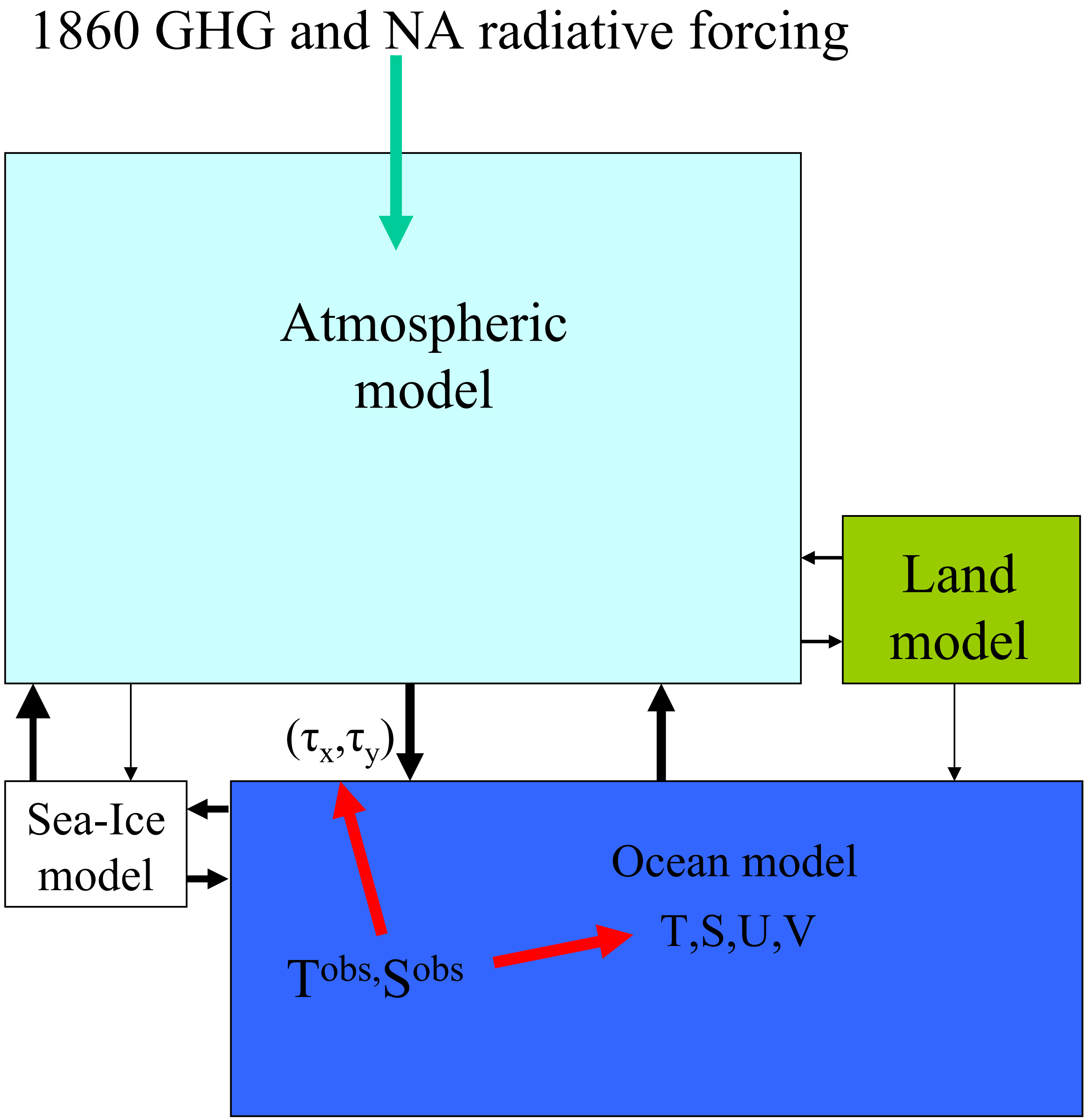
Truth: Historical radiative forcing run from 1861-2000, initializing the model from 300-yr spinup using 1860 radiative forcing

Control: Historical radiative forcing run from 1861-2000, initializing the model from 380-yr spinup using 1860 radiative forcing

25-yr (76-00) mean

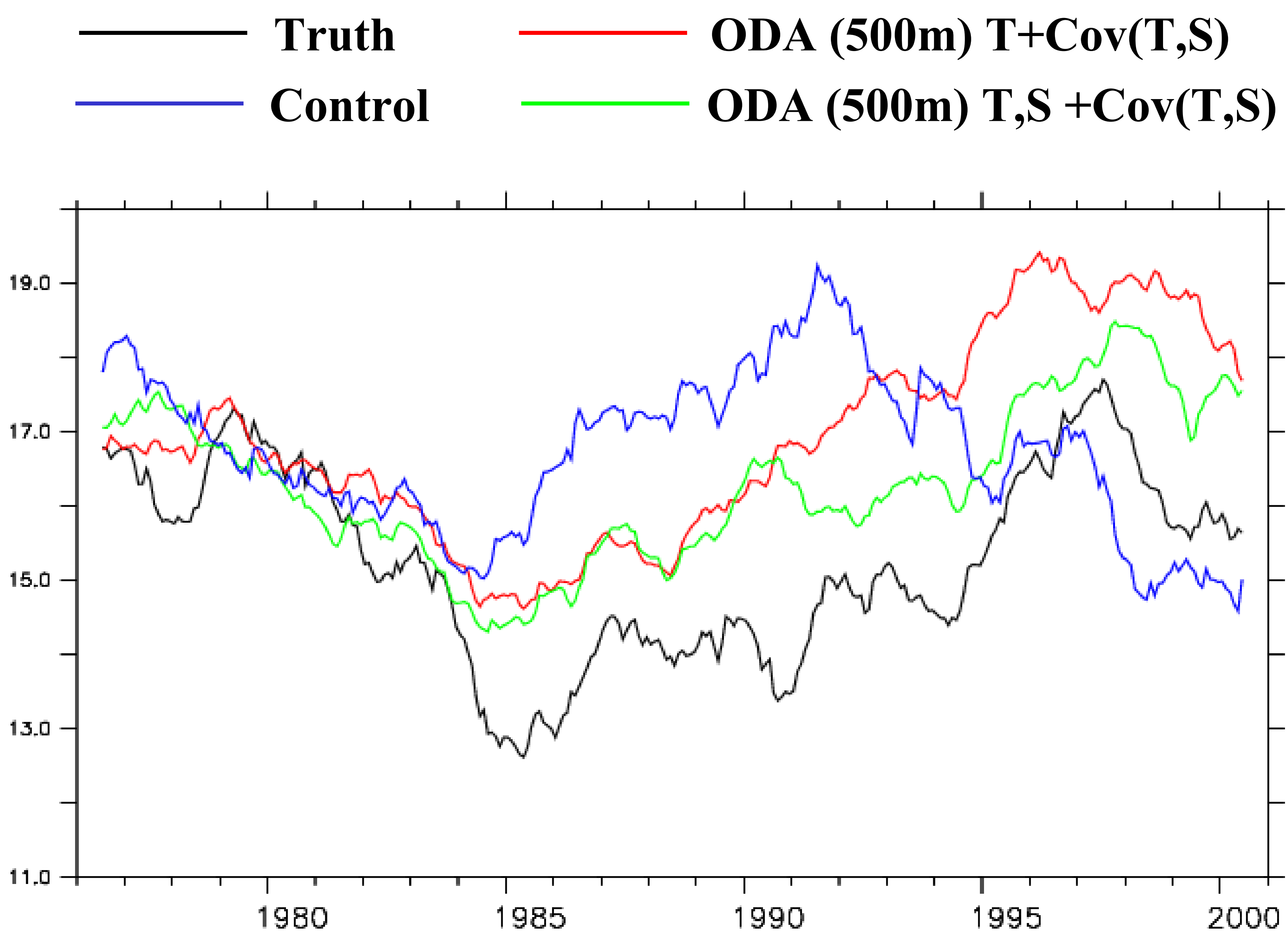




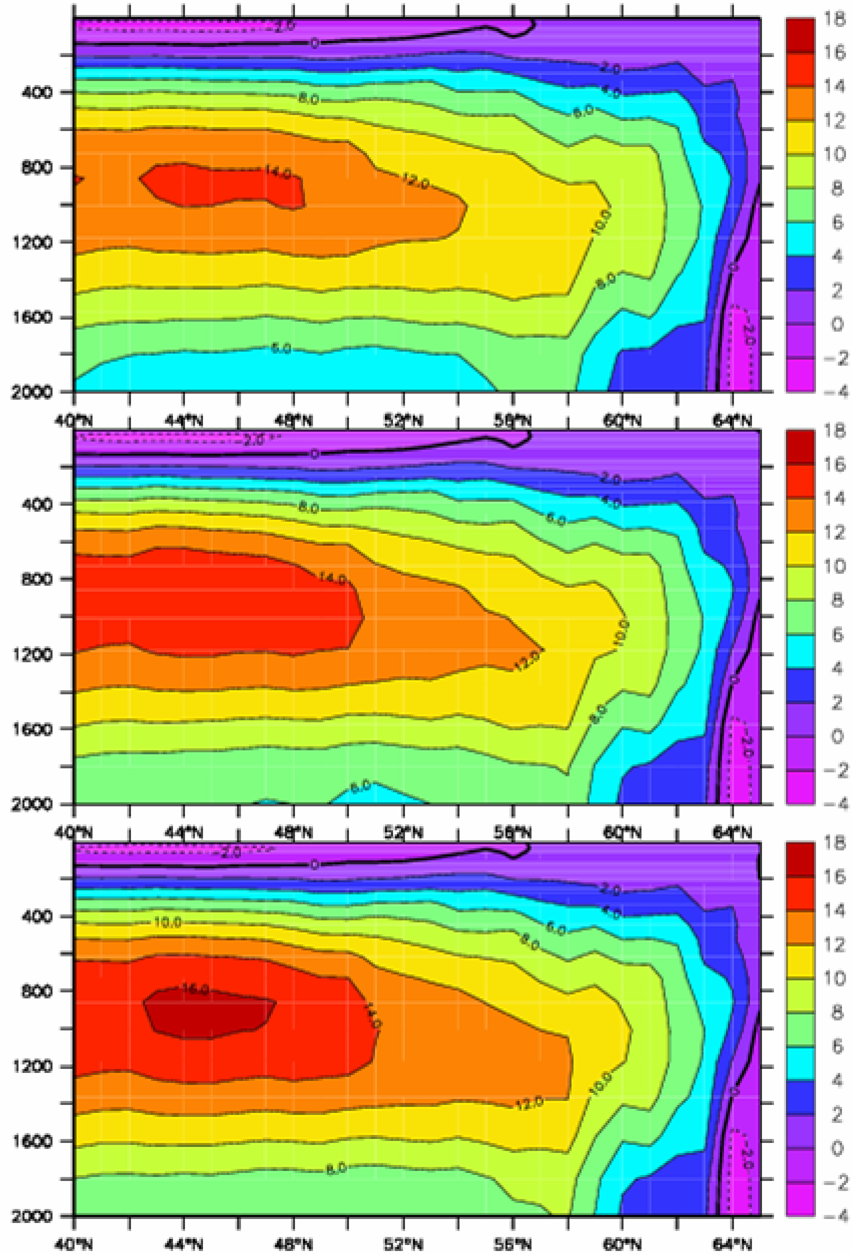


1860 GHG and NA radiative forcing
Atmospheric model
Land model
(τ_x,τ_y)
Sea-Ice model
Ocean model
T,S,U,V
T^{obs}, S^{obs}

13-point running average of Max(ψ) in (40n:70n)



25-yr Time Mean of the Atlantic MOC



Truth

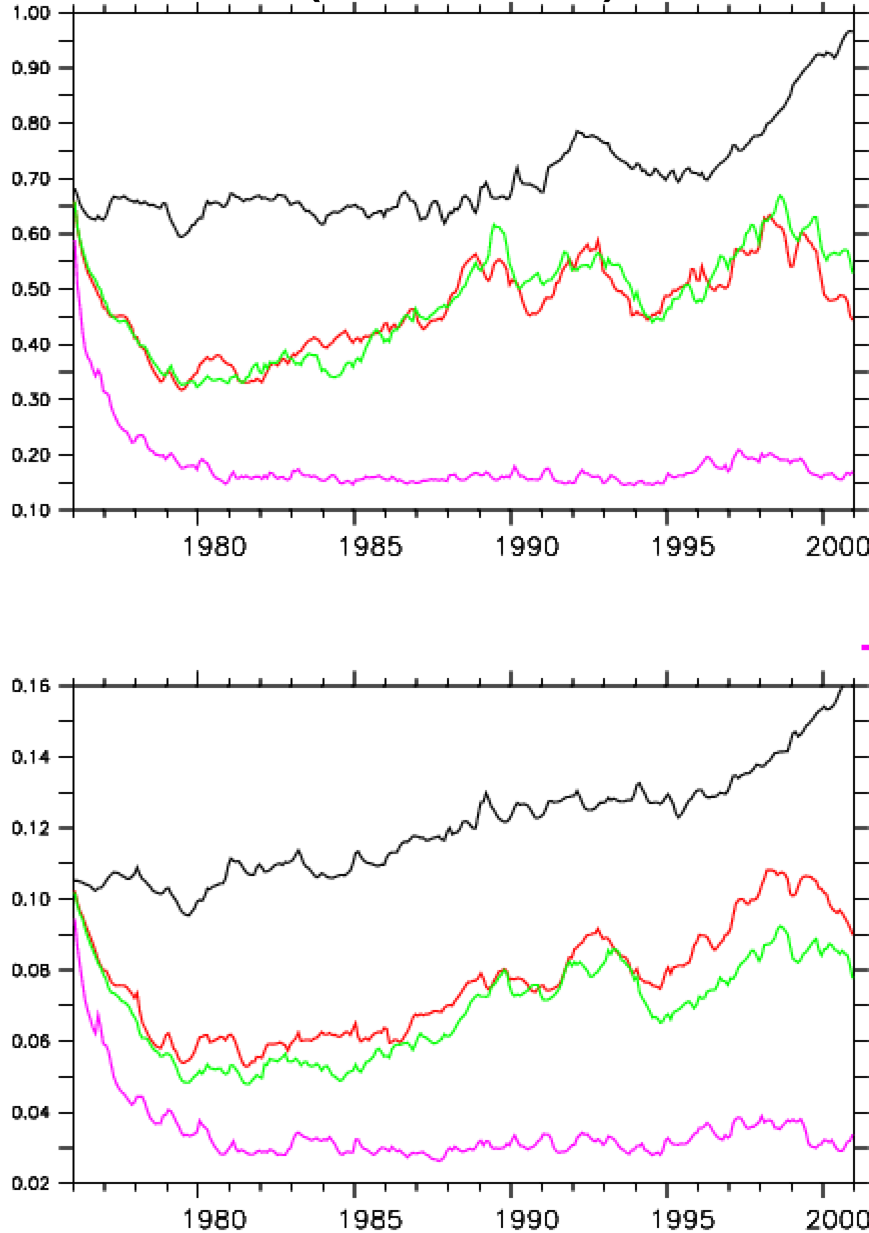
ODA (500m)
T,S + Cov(T,S)

ODA (500m)
T + Cov(T,S)

RMS errors of top 2000 m norh Atlantic (30n:70N)

Temperature (^{o}C)

Salinity (psu)



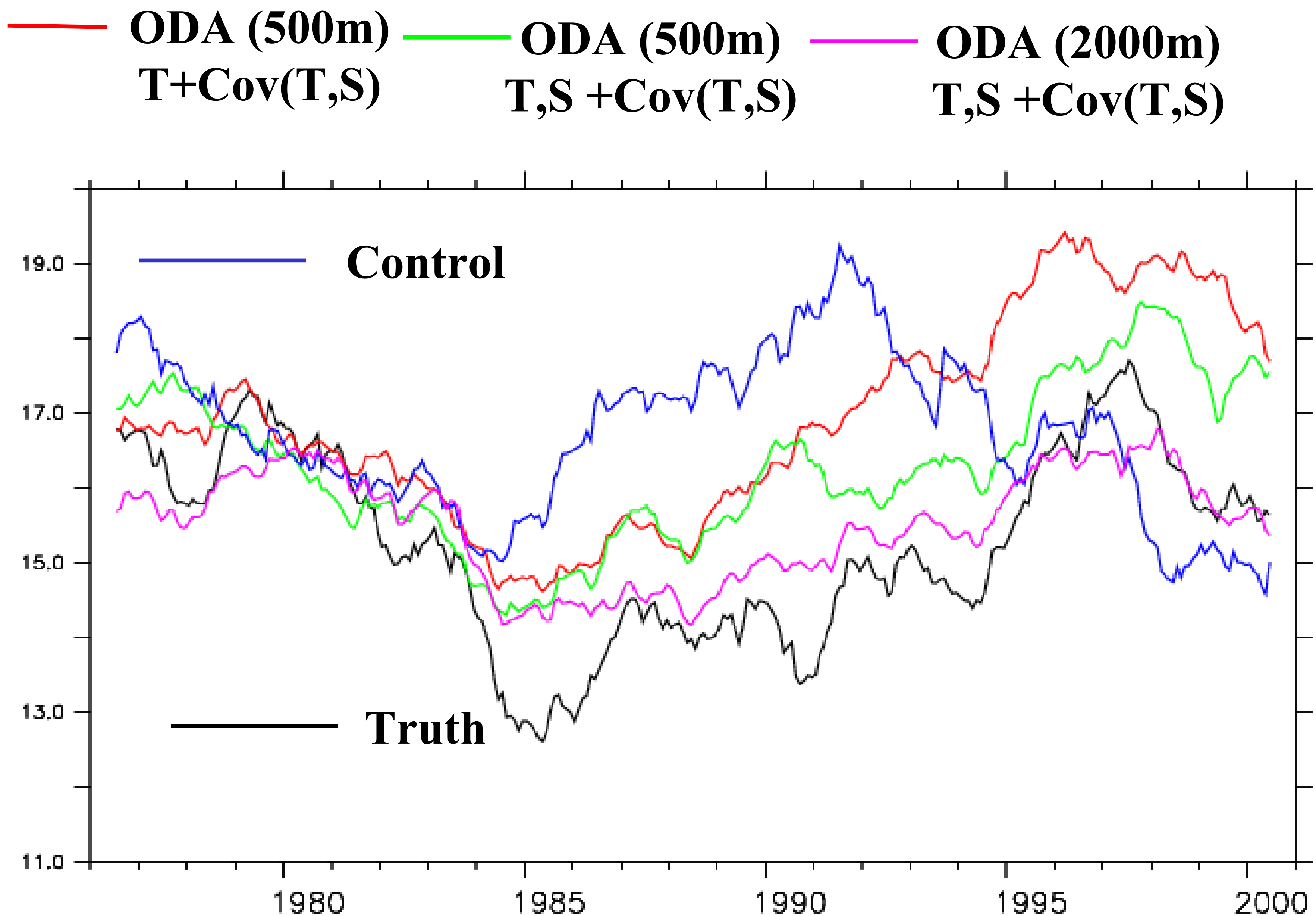
Control

ODA (500m) T+Cov(T,S)

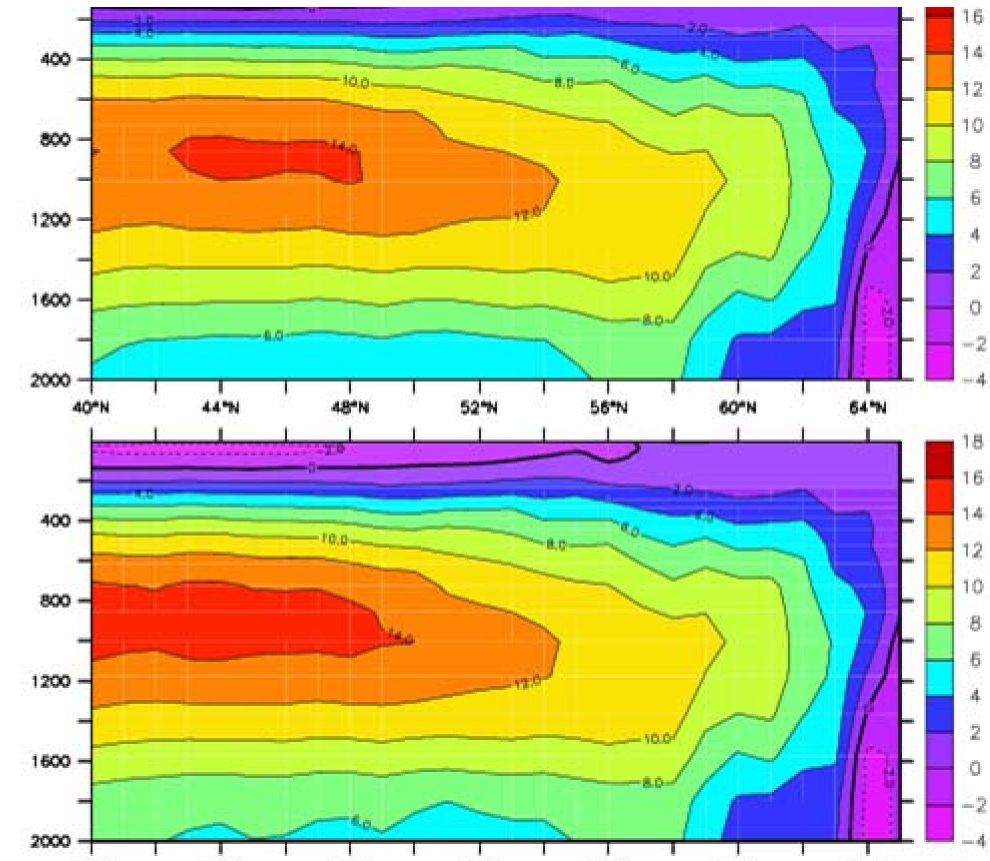
ODA (500m) T,S + Cov(T,S)

ODA (2000m) T,S + Cov(T,S)

13-point running average of Max(ψ) in (40n,70n)



25-yr Time Mean of the Atlantic MOC



Truth

ODA (2000m)
T,S + Cov(T,S)

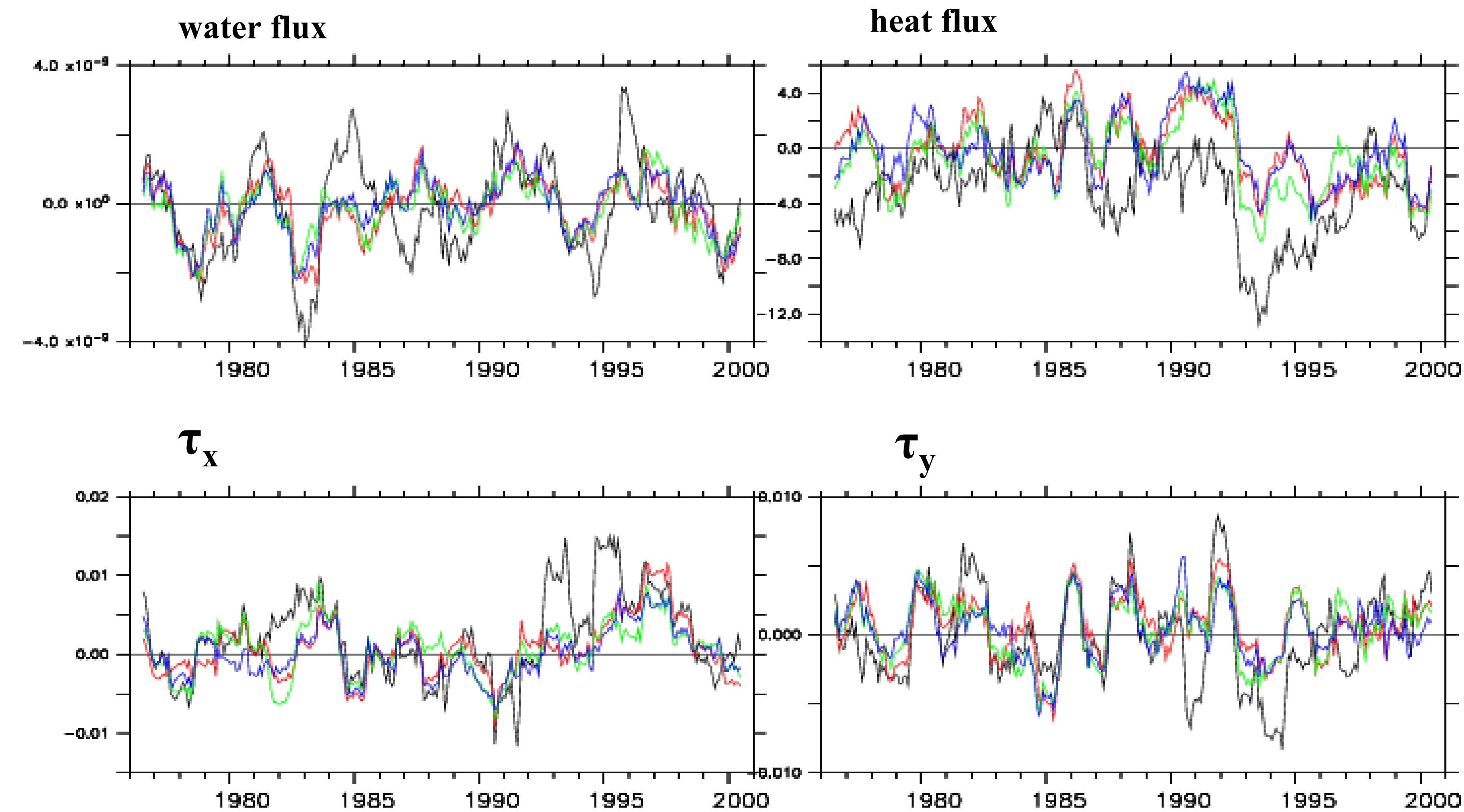
Timeseries of regionally-averaged errors over north Atlantic (30n:70n)

control

ODA (500m) T+Cov(T,S)

ODA (500m) T+Cov(T,S)

ODA (2000m) T,S+Cov(T,S)



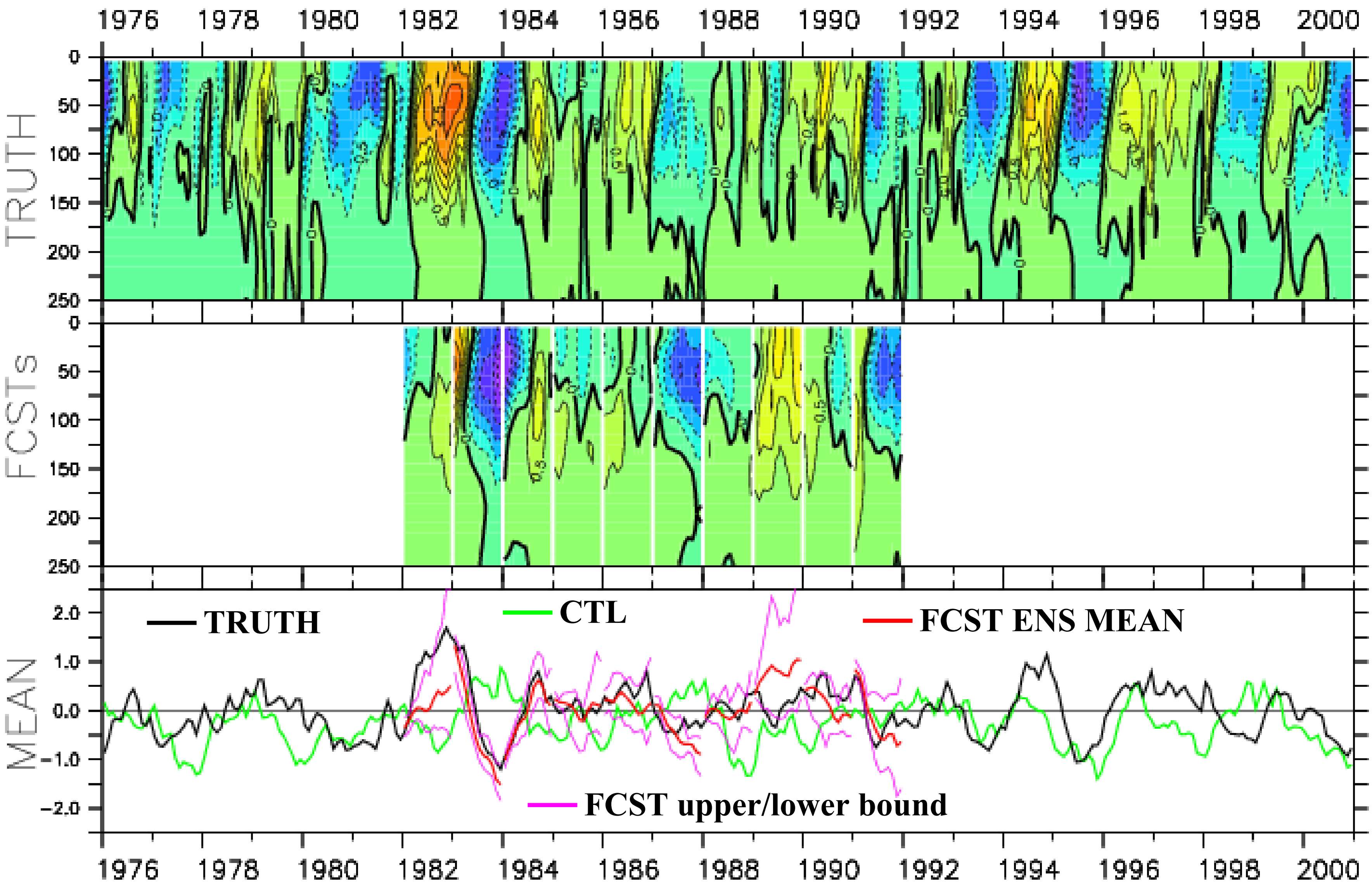
Summary for Climate detection

- ✓ Due to uses of cross-covariance between physical variables, while assimilating obs info the ensemble filter in GFDL's ODA system, to some degree, is able to maintain physical balances in climate evolution, depending on ensemble size, availability of obs ...
- ✓ Given the 20th century ocean temperature observational network, the ODA process in GFDL's CDA system can retrieve the ocean heat content on basin scales after a few year assimilation spin-up.
- ✓ Based on the temperature observational network, uses of T-S covariance greatly improves the tropics. Middle to high latitude improvements were less dramatic, where uses of salinity observations become important.
- ✓ Based on 2005 Argo network and perfect model framework, the GFDL's ensemble CDA system is able to reproduce the large time scale (decadal) trend of the Atlantic MOC by assimilating both ocean temperature and salinity.
- ✓ The variability of the Atlantic MOC is associated with large-scale THC's heat/salt transport, sea surface forcing from atmosphere, fresh water forcing from ice and runoff and their interaction with the NA topography as well. Thus, atmospheric data constraint in the next phase of the CDA experiments would improve the estimate of interannual timescale variability of the Atlantic MOC.

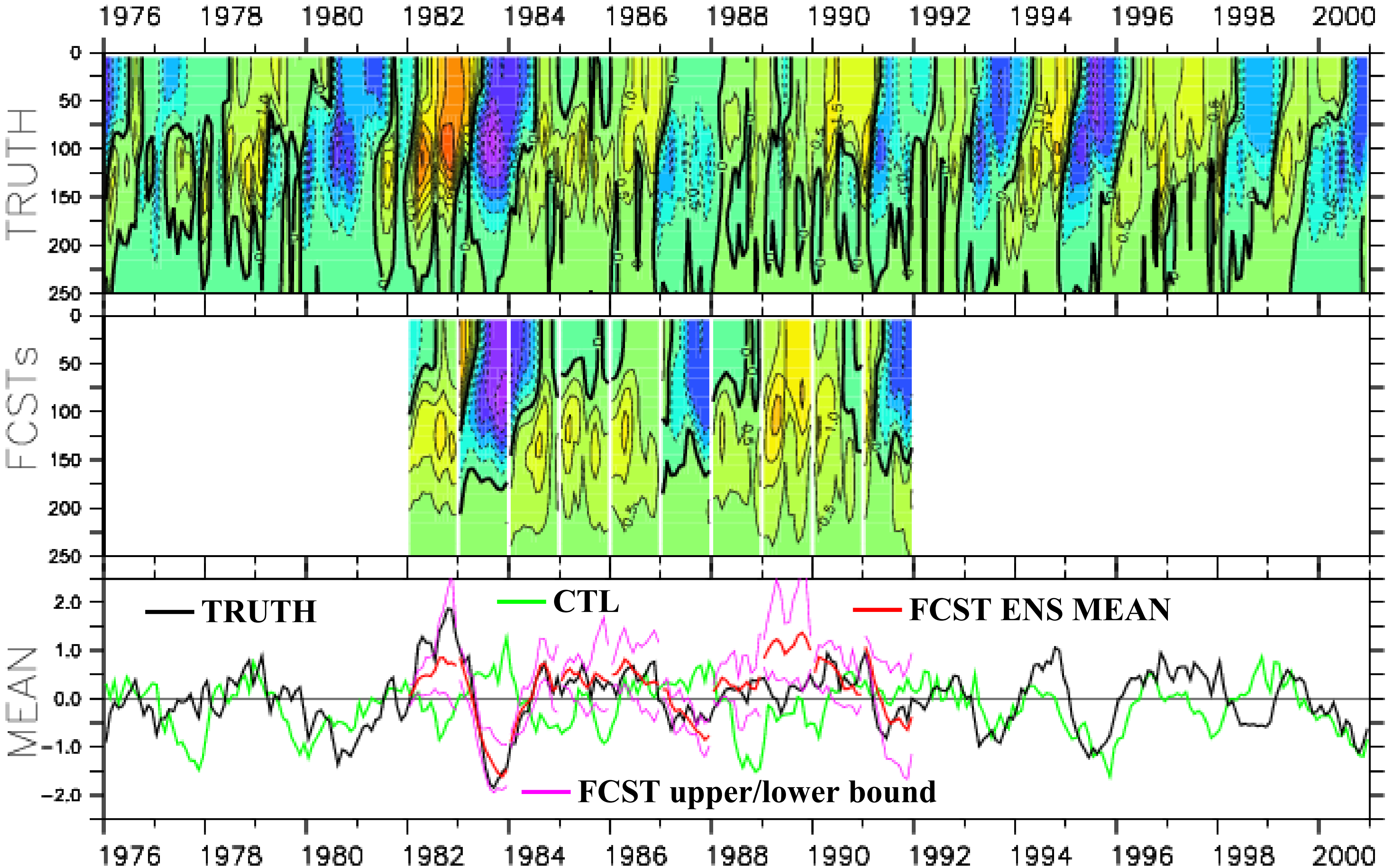
Impact of ODA's initialization for fully-coupled GCM on SI forecasts

✓ 10 forecast cases:
- Vertical structure of NINO3.4, NINO3 and NINO4 temperature
- Forecast skills of SST of NINO4, NINO3.4 and NINO3
- A case study

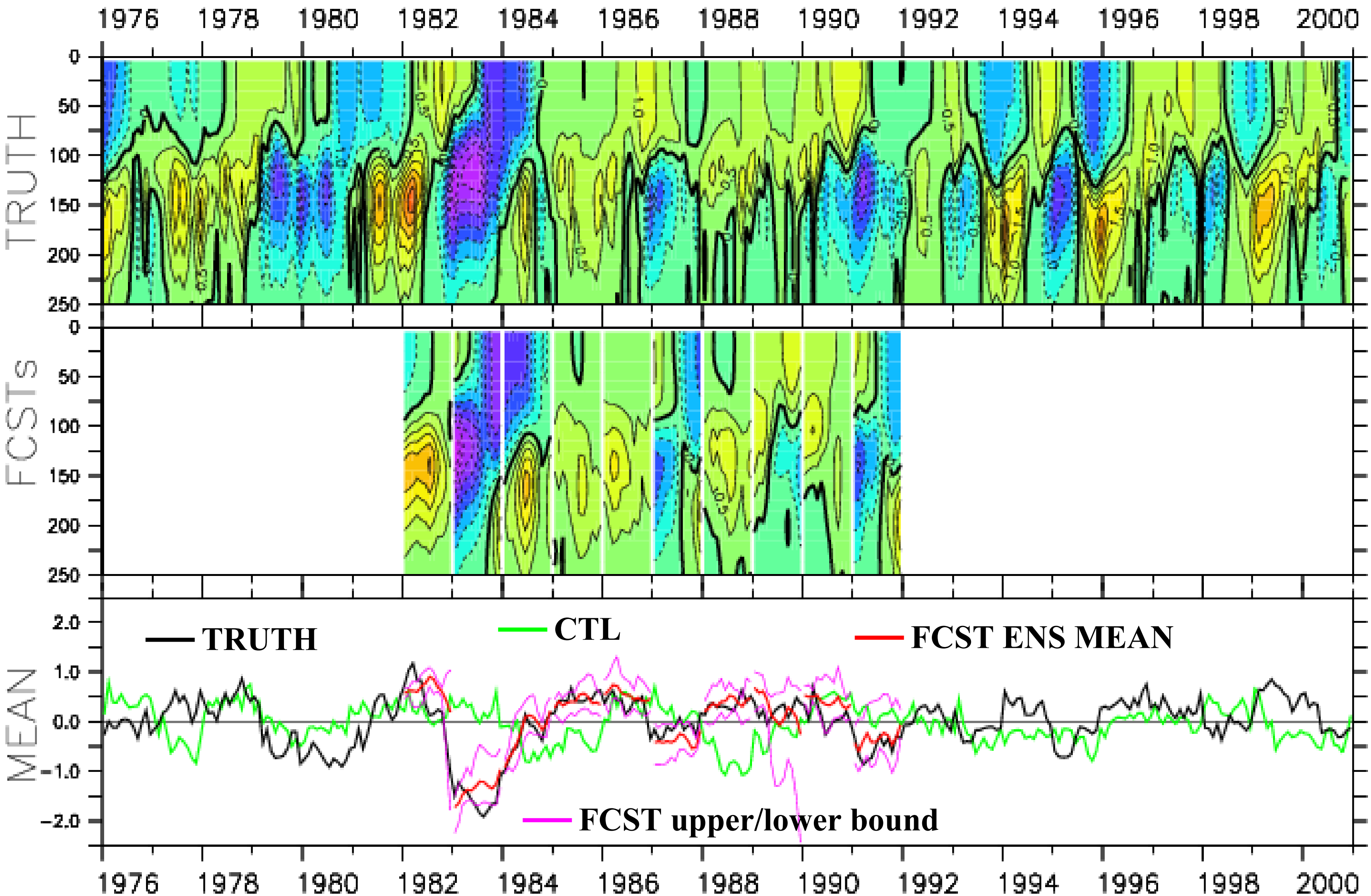
Vertical structure of forecasted Nino3 temperature anomaly



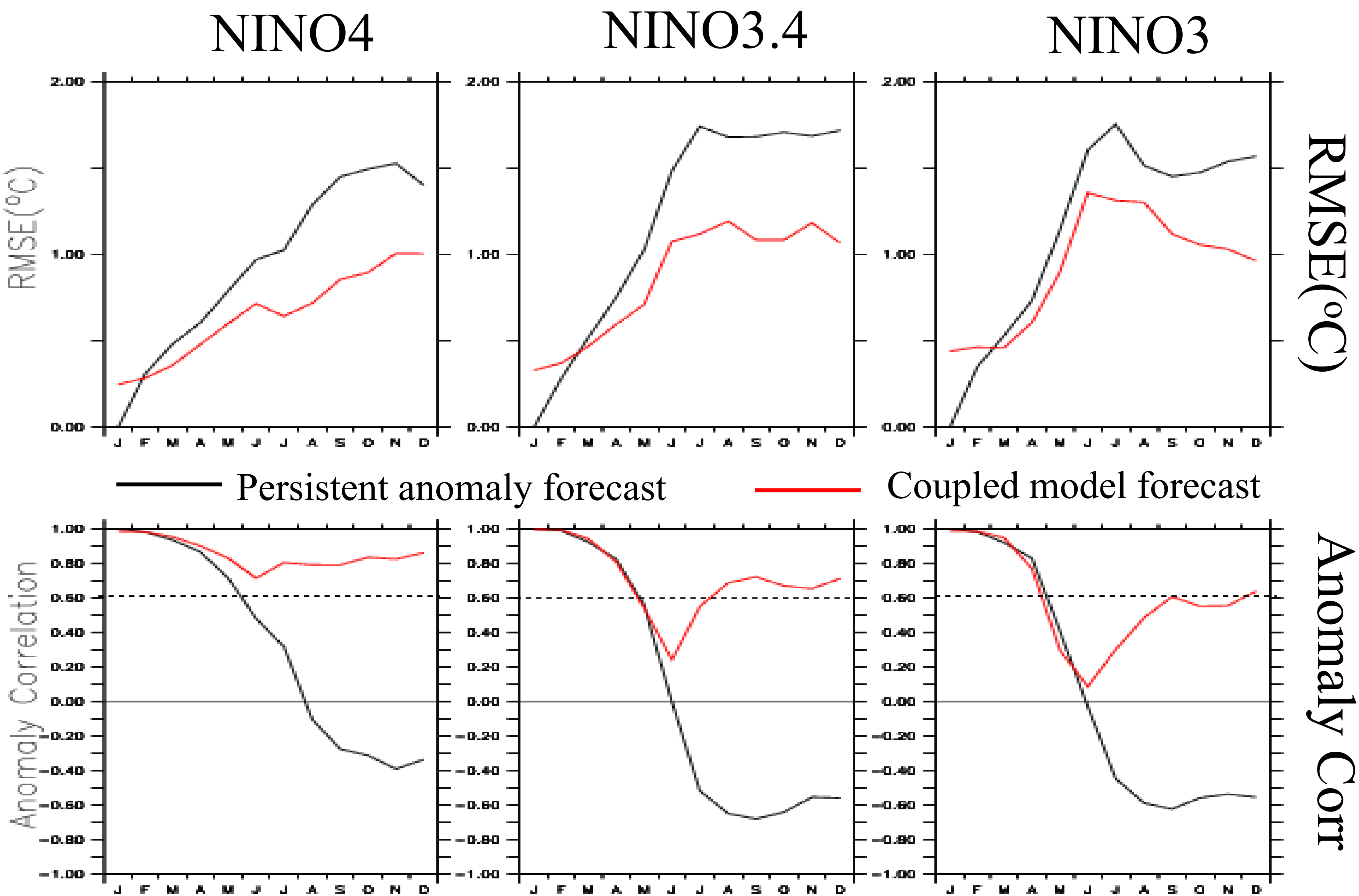
Vertical structure of forecasted Nino3.4 temperature anomaly



Vertical structure of forecasted Nino4 temperature anomaly



SST's forecast skill



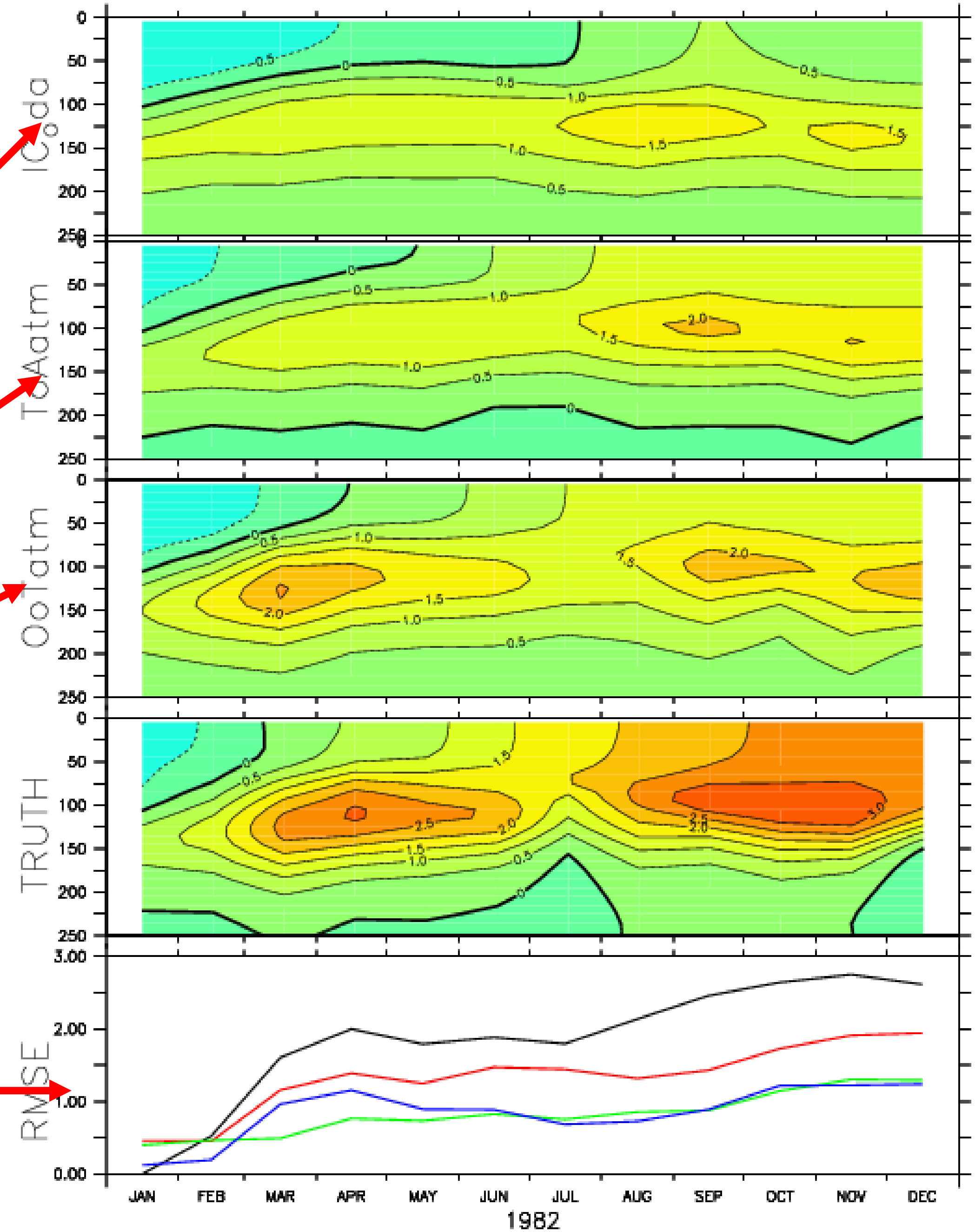
A case study: 1982

Initialize the coupled model from:

- ODA atmos and ocean
- Perfect ocean and ODA atmos
- Perfect atmos and ODA ocean
- Persistent forecast

RMSEs of 4 forecasts

NINO3.4 temperature



Summary for SI forecast experiments

- ✓ The ensemble mean of forecasts initialized from ODA can catch up the warming/cooling trend with a weak amplitude for warming events within one-year forecast
- ✓ Forecast spread increases very rapidly, which implies the atmosphere needs data constrained ICs
- ✓ Skills of forecasts initialized from ODA are much higher than persistent forecasts in the second half year
- ✓ One case study shows based on the oceanic initial conditions from ODA, the improvement of atmospheric initial conditions is very important for the first half year forecast while oceanic initial conditions govern larger timescale signal

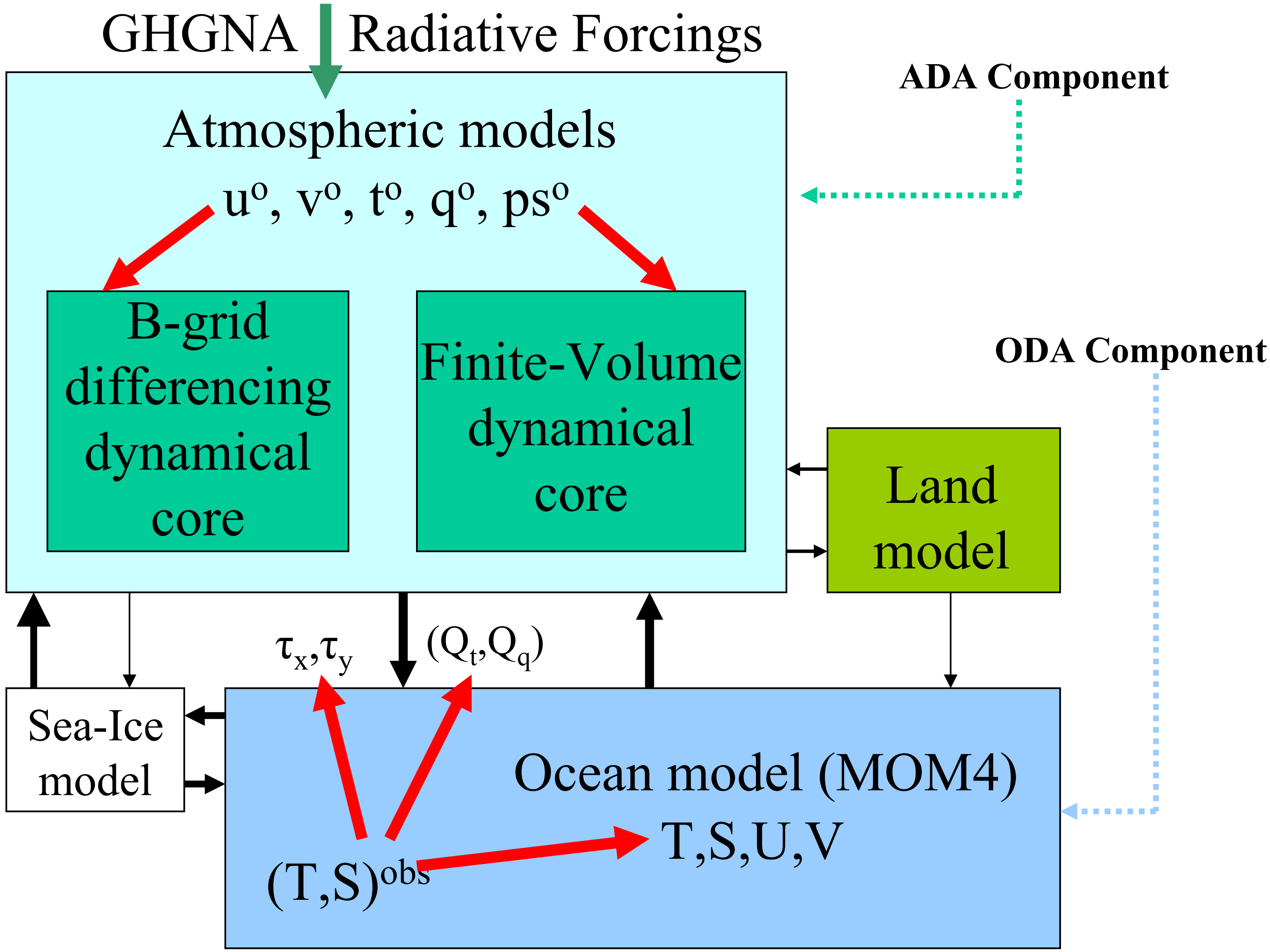
Ongoing experiments for climate detection and forecasts at GFDL

- ✓ Idealized experiments to uncover issues and advance the understanding
  - Atmospheric constraint improves the surface forcing of ocean to refine the estimate of Atlantic MOC and improve SI forecasts
  - Altimetry assimilation (TOPEX,JASON,GRACE)
- ✓ Real data (profiles+satellite data) to reconstruct the history of climate changes in the 20th century, and continuing to …
- ✓ New century for estimating climate states and initializing the SI/decadal forecasts

Challenges

- ✓ Real data – Model biases: more source information + multi-model ‘super’-ensemble
  - Altimetry data; Equatorial current measurements from drifting buoy
  - multi-model ‘super-’ensemble filter (Current: atmospheric B-grid and Finite-Volume cores; Soon: mom4+isopycnal ocean model)
- ✓ Impact of more coupling variable adjustments on ocean states
  - Adjustment of heat/water fluxes using ocean observations within mixing layer
  - Direct constraint on atmospheric boundary by ocean surface observations
  - Direct constraint on synoptic scales from the atmospheric data (using reanalysis, for instance), specially for SI forecasts?
- ✓ How to increase the observation constraint when ensemble spread is very small (deep water, for instance)?
  - A hybrid filter combining stationary/non-stationary error statistics?
  - A 4-dimensional variational ensemble filtering algorithm in which $B = B_0 + B'(t)$, possible?
- ✓ Impact of ensemble size on the accuracy of error covariance estimate
  - 24-member system is running on NASA Columbia cluster (max PEs:2048)
  - Daily atmospheric disturbance as ensemble perturbation

GFDL's Ensemble Data Assimilation System Using Multi- Coupled Climate Models



Long Term Efforts …

- ✓ Improve climate variability analysis (Carbon/heat uptake, circulation, …)
- ✓ Improve forecast (SI, decadal/multi-decadal) by improving initialization
- ✓ Detection of climate change
- ✓ Analysis estimate of variables in sea ice and land model (ice mass, run-off etc., for instance)
- ✓ Observing system evaluation/design
- ✓ Model evaluation/verification for improving modeling
- ✓ Model parameter estimation

Thanks to …

- ✓ Balaji for supports on domain decomposition and communication, computer resources on Columbia
- ✓ Jeff Anderson for helpful discussions on filtering, and early discussions on filtering parallelization
- ✓ Andrew for persistent helps on visualization and generous discussions on physical oceanography
- ✓ Fengrong, Mike, Hyun-Chul for helps on cm2's configurations; Zhi, Hans for helps on NCO and mppnccombine utilities; Jianjun and Jian for helpful discussions
- ✓ All GFDL staff for efforts on climate modeling